UNCLASSIFIED

Australian Government

Department of Defence
Science and Technology

A Ship Performance Modelling and Simulation Framework to Support Design Decisions throughout the Capability Life Cycle: Part 1 – Risk Mitigation and Requirement Setting

Dylan M. Dwyer and Brett A. Morris

Maritime Division
Defence Science and Technology Group

DST-Group-TR-3532

ABSTRACT

Modelling and Simulation (M&S) presents the opportunity to support Australian Department of Defence endeavours toward becoming a smart buyer in naval vessel acquisitions. Evaluating ship performance using M&S allows capability design activities to be conducted early during the Risk Mitigation and Requirement Setting phase of the Australian Capability Life Cycle (CLC). These activities support an improved understanding of a design space based on robust analysis that can be used by acquisition stakeholders to develop requirements and aid defensible design trade-off decisions. This report proposes an M&S framework for evaluating ship performance in support of Royal Australian Navy acquisitions. The M&S framework facilitates generation of an indicative design space for a defined capability need. Exploring this design space, acquisition stakeholders gain knowledge of a more thorough definition of requirements. Implementing the M&S framework ensures that the requirements released to industry, the primary output of this phase of the CLC, constrains the technical solutions to only those Off-the-Shelf designs that adequately meet the capability need. Thereby, the M&S framework can contribute to Defences ambition of becoming a smart buyer in an Off-the-Shelf naval vessel acquisition.

UNCLASSIFIED

Produced by

Maritime Division
Defence Science and Technology Group
506 Lorimer Street,
Fishermans Bend VIC 3207

Telephone: 1300 333 362

September 2018
AR-017-284

APPROVED FOR PUBLIC RELEASE

A Ship Performance Modelling and Simulation Framework to Support Design Decisions throughout the Capability Life Cycle: Part 1 – Risk Mitigation and Requirement Setting

Executive Summary

The Australian Department of Defence (ADOD) has adopted a smart buyer approach for Defence acquisitions to maximise capability and value for money for the Australian taxpayer. In the context of Royal Australian Navy (RAN) ship acquisitions, two guiding principles were adopted in light of the smart buyer approach: selecting a mature design and limiting the amount of Australian design changes. Stemming from these two principles, Defence has adopted an Off-the-Shelf (OTS) acquisition strategy for their surface ship capability needs. Reinforcing the smart buyer approach, the ADOD has the opportunity to utilise advances in Modelling and Simulation techniques to support definition of fit-for-purpose requirements in a robust and repeatable manner. Consequently, the requirements released to industry ensure only the most suitable OTS ship designs with respect to the capability needs will be received for down-select.

Modelling and Simulation (M&S) presents the opportunity to support the ADOD endeavours to become a smart buyer by facilitating capability design activities. Capability design activities conducted early during the Risk Mitigation and Requirement Setting phase of the Australian Capability Life Cycle (CLC) support an improved understanding of the design space. Knowledge gained can be used by acquisition stakeholders to assist development of requirements and aid design trade-off decisions.

In this report a ship performance M&S framework for RAN vessel acquisitions is proposed. The M&S framework facilitates generation and exploration of a design space based on defined naval vessel capability needs. The M&S framework can be aligned with a Model-Based Systems Engineering (MBSE) methodology to facilitate traceability between requirements, design variables and ship performance. A case study is presented for application of the M&S framework during the Risk Mitigation and Requirement Setting phase. The case study involved the acquisition of an indicative hydrographic survey capability into the RAN. The aim of the study was to analyse the impact of vessel type and hullform design for the suitability to meet an optimal hydrographic survey capability. Key Performance Parameters (KPPs) were derived from an exemplar mission scenario. Three KPPs were established relating to the launch and recovery seakeeping performance, transit based seakeeping performance, and resistance at transit speed. Design spaces of three different vessel types were considered for meeting the capability needs: a hydrographic survey vessel (HSV), an offshore patrol vessel and a frigate.

Results showed that the HSV hullform achieved optimal performance based on the three KPPs. Further analysis of the hullform was conducted to gain an understanding of the hull design variables that contributed to optimal performance. Results showed that the vessels length and length/beam ratio had the greatest influence on all three KPPs in various sea

states. Consequently, increasing vessel length and decreasing the vessels length/beam ratio contributed to improved performance of all KPPs. It was shown how an understanding of the relationship between design variables and KPPs, and the strength of these relationships could assist acquisition stakeholders during the requirements definition process and support design trade-off decisions.

Knowledge gained from exploration of the HSV's design space was used to scrutinise the existing Off-the-Shelf (OTS) naval vessel marketplace and assist in identification of possible capability risks. OTS designs were ranked based on their likely mission performance according to relationships established from exploration of the design space, discussed above. This capability design activity was able to highlight the improvement in performance of an optimised hullform as opposed to those in the current marketplace. Comparing results of the top ranked OTS naval vessels to those optimised hullforms from the generated design space, capability risks as a result of any performance gaps were able to be identified. Understanding the significance of these capability risks could drive requirements for design changes to ensure a design is fit-for-purpose. If design changes are affordable, it is logical to pursue modifications that could increase performance of the KPPs for the naval vessel being acquired. If the capability risk is too high, that is a performance gap has been identified, the requirements released to industry could drive necessary design changes to minimise the gap in performance. Otherwise, requirements should reflect the combination of parameters that contribute to improved mission performance.

Implementing the Ship Performance M&S framework during the Risk Mitigation and Requirement Setting phase of the CLC provides acquisition stakeholders with an improved understanding of a design space for a proposed capability need. Through application of the case study, it was demonstrated how the ship performance M&S framework could be used in a robust and repeatable manner. Knowledge gained from implementing the M&S framework assists acquisition stakeholders with requirements setting activities and aids defensible design trade-off decisions. Conducting these capability design activities ensures the requirements released to industry represent only the most suitable OTS ship designs with respect to the capability needs. Therefore, applying the ship performance M&S framework during this phase of the CLC can contribute to Defence's ambition of becoming a smart buyer in an OTS naval vessel acquisition.

Authors

Dylan M. Dwyer
Maritime Division

Dylan joined Defence Science and Technology Group in 2016 as a graduate after receiving a Bachelor of Engineering in Naval Architecture (Honours) from the Australian Maritime College, University of Tasmania. He works under the discipline of Platform Concepts Analysis and Requirements Exploration. In his time at DST Group Dylan has developed, and is continuing to expand his knowledge of modelling and simulation techniques, and systems engineering practices in the domain of naval ship conceptual design and requirements exploration. Dylan is currently undertaking part-time studies towards a Masters in Systems Engineering at the University of New South Wales.

Brett A. Morris
Maritime Division

Brett is a Naval Architect/Systems Engineer who joined the Defence Science and Technology Group in 2007. He has previously worked for the RAN in the Directorate of Navy Platform Systems and has conducted research in the fields of Naval ship concept design, modelling and simulation of ship performance, along with Model-Based Systems Engineering. Brett has a Graduate Diploma in Systems Engineering, a Bachelor of Engineering (Naval Architecture) and is currently undertaking part-time research towards a PhD.

This page is intentionally blank.

Contents

Glossary

ADOD	Australian Department Of Defence
ASSET	Advanced Surface Ship Evaluation Tool
CLC	Capability Life Cycle
C&RE	Concepts and Requirements Exploration
DOE	Design Of Experiments
DRM	Design Reference Mission
DWP	Defence White Paper
DWT	Dead-Weight
FIC	Fundamental Inputs to Capability
FPR	First Principles Review
HGM	Hull Generation Model
HS	Hydrographic Survey
HSV	Hydrographic Survey Vessel
KPP	Key Performance Parameter
L&R	Launch and Recovery
MBSE	Model-Based Systems Engineering
MII	Motion Induced Interruptions
MOE	Measure of Effectiveness
MOP	Measure of Performance
M&S	Modelling and Simulation
OA	Orthogonal Arrays
OCD	Operational Concept Document

OPV	Offshore Patrol Vessel
OTS	Off-the-Shelf
RAN	Royal Australian Navy
ROV	Remotely Operated Vehicle
RSM	Response Surface Model
R_T/Δ	Total Resistance per tonne Displacement
SE	Systems Engineering
SME	Subject Matter Expert
SS	Sea State
STOVL	Short Take-Off and Vertical Landing
VTOL	Vertical Take-Off and Landing

1. Introduction

The *2016 Defence White Paper* (DWP) stated the Australian Government requires Defence to become a smart buyer to 'maximise Defence capability and value for money for the Australian taxpayer' [1]. The Australian Defence Organisation's (ADOD) adoption of the smart buyer approach was a key recommendation from the First Principles Review (FPR) [2]. Following the release of the FPR and 2016 DWP, the Government released its Naval Shipbuilding Plan [3]. Amongst the guiding principles for the Plan's implementation, two reforms are expected to be implemented by Defence during naval vessel acquisitions [3: p.105]:

1. A mature design is selected at the start of the build; and,
2. The amount of Australian design changes are limited.

These reforms appear to be primarily due to the current constraints of the ADOD's design and engineering workforce, as well as the availability of financial resources. Stemming from these two principles, Defence has adopted an Off-the-Shelf (OTS) acquisition strategy for the surface ship capability needs identified in the DWP. The OTS acquisition strategy is likely to remain the default approach for ADOD naval surface vessels in the foreseeable future.

The naval capability needs set out in the DWP means the Royal Australian Navy (RAN) is amidst the 'greatest recapitalisation…since the Second World War' [3: p.11]. The recapitalisation has resulted in a continuous shipbuilding strategy to support naval vessels throughout the entire Capability Life Cycle (CLC). It was highlighted by RAN capability managers that 'being a Smart Buyer is a fundamental requirement to the achievement of being a Smart Owner and ultimately the achievement of Navy's continuous shipbuilding objective' [4: p. 30]. The continuous shipbuilding strategy relies heavily on a relationship between Defence and industry through RAN's OTS acquisition approach. Defence industry establishes this relationship during the early stages of the CLC by providing technical solutions for naval vessel acquisitions. At this stage of the CLC the ADOD must become a 'smart buyer'[1] to ensure the technical solution is fit-for-purpose with respect to the capability needs. After acquiring the naval vessel, and for the remainder of the CLC, the ADOD must become a smart owner to ensure, for the service life of the naval vessel, that the capability is maintained.

Modelling and Simulation (M&S) presents the opportunity to support the ADOD endeavours to become a smart buyer and consequently a smart owner by facilitating capability design activities. Performing capability design activities throughout various key

[1] The authors use the FPR definition of a 'smart buyer', which in turn was borrowed from the United States Government Accountability Office, rather than later interpretations. 'A smart buyer is one who retains an in-house staff who understands the organisations mission, its requirements, and its customer needs, and who can translate those needs and requirements into corporate direction. A smart buyer also retains the requisite capabilities and knowledge to lead and conduct teaming activities, accurately define the technical services needed, recognise value during the acquisition of such technical services, and evaluate the quality of services ultimately provided.' [2: p.33]

stages of the CLC supports an improved understanding of the naval vessel as a system. This gain in knowledge can be used to inform capability stakeholders of requirements and design trade-off decisions. The outcome of this process will contribute towards the improved mission suitability of the naval vessels that are acquired and throughout their lifecycle. To enable this process of knowledge building throughout the scope of the CLC requires the development of a comprehensive, flexible and robust M&S framework. Such a framework can be implemented at key stages of the CLC to inform capability stakeholders for various important decisions.

After completion of the Force Design Process during the *Strategy and Concepts* phase of the ADOD CLC, the M&S framework can be used during the *Risk Mitigation and Requirement Setting* phase to support requirements setting [5]. At this stage, M&S can facilitate design activities to support an improved understanding and more rigorous definition of requirements. This iterative process has been termed 'requirements elucidation' [6], the result of which, is that the requirements released to industry constrain the technical solutions to those that adequately meet the capability need. In an OTS naval vessel acquisition this ensures only suitable designs are received from Defence industry for consideration during tender evaluation. Hence, implementing M&S at this stage of the CLC contributes towards RAN's smart buyer approach for acquisition.

Following the *Risk Mitigation and Requirement Setting* phase, implementing M&S during the *Acquisition* phase presents the opportunity to support the RAN as a smart owner. The initial stages of *Acquisition* present the opportunity to perform final design activities to support the introduction of a fit-for-purpose design into service. A vital step in this process is ensuring the acquired design addresses the defined requirements, and the design's safety and suitability for service [5]. Accompanying this process, capability stakeholders perform detailed design by adapting the acquired design specifications. Here, M&S can be implemented to support the detailed design process by facilitating tailored design activities. The outcome of which, can be used as a means to justify in a robust manner, high-value design changes prior to the introduction of the vessel into service, optimising project execution and enabling the RAN's ambitions towards becoming a smart owner [4].

The final phase of the CLC, the *In Service and Disposal* phase, offers the opportunity to implement M&S to support capability managers maintain capability relevance and availability through life. Often, this requires a vessel's subsystem's (e.g. weapons and Command and Control) to be upgraded to some degree in order to maintain a strategic military advantage. Upgrades are performed in two manners: un-planned and pre-planned. Un-planned upgrades are primarily due to a realisation of a decline in relative capability effectiveness generally from new and emerging threats or unexpected system performance. Planned upgrades are due to a technology refresh of relevant dynamic subsystems [4: p.8], commonly termed mid-life-upgrades. Irrespective of the manner for an upgrade, M&S can be used to gain an understanding of the increase in capability effectiveness and any associated risks by facilitating design activities. Supporting in-service upgrade considerations through M&S can optimise the execution of the upgrade process, identify high-value subsystem upgrades and investigate the feasibility of technology insertion for a given vessel. Subsequently, upgrade timelines can be reduced -

minimising the temporary loss of a capability, and it can be reassured the vessel's capability effectiveness is maintained through life, therefore contributing towards becoming a smart owner.

Based on the aforementioned observations, the Maritime Division of the Defence Science and Technology (DST) Group has undertaken research to develop an M&S framework that can support surface ship acquisition and through life management decisions by the RAN. The development and application of this M&S framework is covered in three parts. This report, part one, discusses the development of a Ship Performance M&S framework for application of RAN vessels throughout the *Risk Mitigation and Requirement Setting* phase of the ADOD CLC. Parts two [7] and three [8] cover the *Acquisition* and *In-service and Disposal* phases of the ADOD CLC respectively. The three reports and their demonstrated applications for use throughout each phase of the CLC are summarised in Figure 1.

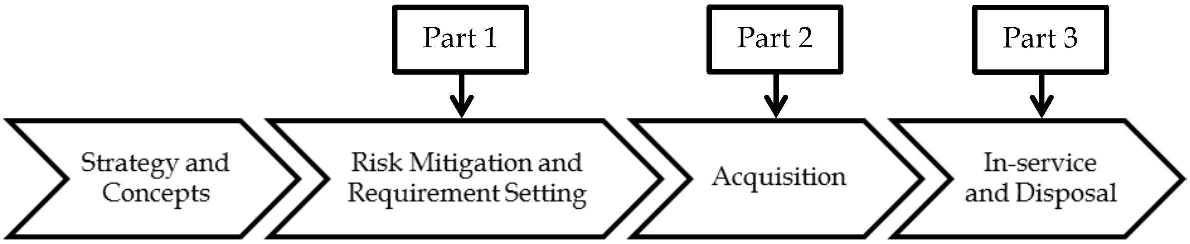

Figure 1. Summary of the three reports detailing their demonstrated applications for use within each of the final three phases within the ADOD CLC

Each of the three reports will step through, by each of the highlighted phases of the CLC, a demonstration of how the Ship Performance M&S framework can be tailored and adapted to allow capability design activities, relevant to each phase, to be performed to aid decision-making. Thereby, demonstrating how the M&S framework can assist the RAN as a smart buyer and owner, and ultimately helping Navy achieve its continuous shipbuilding objective.

1.1 Background

This background covers a literature review of established and reputable conceptual ship design tools that have been used in naval vessel acquisition environments. The aim of the background is to outline aspects of each tool's applicable for use within the RAN's OTS acquisition approach.

The naval ship development process is presented with the challenge of designing a complex system of interdependent sub-systems that interact and influence each other to varying degrees. Optimising the capability of the ship system involves designing, trading-off, selecting and integration of sub-systems in a multifaceted design environment. Complicating the design process further, designers must consider the scope in capability of a system able to meet a wide variety of mission scenarios or operational situations. Additionally, designers must consider the change in capability over time due to emerging threats and technologies that result in a decline of the systems mission effectiveness. These physical design challenges are exacerbated by the need to account for a range of sometimes competing objectives, as well as the scrutiny associated with spending taxpayer's money. Capturing these aforementioned complex matters in a structured and systematic naval vessel design process has been met by design communities through the advancements of computer-based technologies, as well as case studies presented in the open literature addressing the design of complex systems [9].

An early example of employing computer-based technologies to assist with the naval ship design process is the US Navy's Advanced Surface Ship Evaluation Tool (ASSET). ASSET was proposed in 1984 to support the rapid and systematic evaluation of existing and emerging technologies on the configuration and performance of naval surface ships in a bespoke design environment [10]. It is an interactive tool comprised of computational modules that integrate engineering standards and practices, analysis methods, historical data and technology products into a single design environment [10]. The purpose of ASSET is to perform feasibility and conceptual ship design studies, considering the whole ship system by incorporating technical naval architecture disciplines of early stage vessel design as the computational modules. The generated concept vessel designs are relatively detailed with respect to the amount of available knowledge typical designers have at commencement of a naval ship design process. ASSET relies on an extensive and detailed historical database to enhance the knowledge building process. Having the capacity to evaluate such a detailed concept design is advantageous since it reduces risk and cost overheads for the projects progression into detailed design, construction and acquisition. For national defence organisations that are resource and finance restricted, such as the ADOD, the resources required to develop such an evaluation tool as ASSET are unlikely to be available. Instead, the knowledge building phase to support requirements elucidation in the early stages of vessel design must rely on system development approaches better suited to resource constrained environments.

Utilising advancements in computer technology Andrews [9] proposed a concept design methodology for naval vessels that employed a functional building block approach to support knowledge building during the initial stages of design. The design process is based on decomposing the systems capability into functional groups, namely, float, move, fight and infrastructure [6]. Building blocks are then identified by functions, for example, the hull-structure building block relates to the float function. With interaction from the human designer, these 3D building blocks that contain all attributes necessary for placing demands on the ship are rationally configured. A hydrodynamic skin, representative of the hull, is then wrapped around the building blocks to form a model of the concept design [9]. This process can be utilised to optimise the capability by reconfiguring the arrangement of the building blocks. The approach uses Systems Engineering (SE) thinking which allows the designer to gain a clearer understanding of requirements prior to searching for solutions. At the initial stages of design this allows for a solution-independent approach, ensuring the widest range of ship designs can be explored for suitability to meet the capability needs [11]. This approach demonstrated the advantages of using SE thinking as part of a naval vessel design process. However, a design approach such as this is too tightly coupled to be an efficient means for aiding the wide array of design decisions relating to various ship characteristics, of which there are various attributes, and that are all shaped by their overarching capability needs. Such an approach requires the development of a highly interconnected whole-of-ship system to be synthesised prior to being useful to decision-makers. This approach would prove inefficient for assisting the decisions that need to be deliberated early in OTS acquisitions. For example, what is the trade-off between length and seakeeping performance?

Applying the progress of knowledge in systems engineering throughout the latter decades of the 20th century, Brown and Thomas [12] proposed a naval vessel concept design process for rational selection of concepts based on critical objective attributes, namely cost, risk and mission effectiveness. The process employs a Model-Based Systems Engineering (MBSE) approach to maintain traceability of a Design Reference Mission (DRM) that is linked to a design space. This link is enabled through establishing Measures of Effectiveness (MOEs) that are elaborated from operational scenarios captured in the DRM. Measures of Performance (MOPs) are then decomposed or derived from the MOEs and define the performance of a particular ship function. Functional breakdown of the problem in this manner is typical of common SE practices [13]. Importantly, this approach enables the designer to conduct capability design activities in an informed manner, highlighting the relationship between aspects of ship design to operational effectiveness [14]. Winyall, Edwards [15] applied the approach for a multi-objective optimisation of a 3D hullform problem. Through application of commercial MBSE and 3D modelling software it was shown how relationships between ship hullform design parameters and performance could be established. It was then demonstrated how the hullform could be optimised for multiple performance objectives based on the information these relationships provided. The approach proposed by Brown and Thomas [12] demonstrates the benefits of utilising modern day SE practices to support design decisions during naval vessel concept design. However, these approaches utilise operational effectiveness models to simulate the DRM that can require significant effort to develop [16]. Furthermore, and this is the case with the latter ship design tools design decisions need to be made not only in the initial stages of the capability's lifecycle, but also throughout the remainder.

Also employing MBSE practices, Morris and Sterling [17] constructed an approach to provide traceability between Defence's strategic objectives and system operational objectives in an ADOD context. Originally, the approach was not system specific, though its application was best demonstrated and suited for OTS procurement environments in the RAN [18]. Dissimilar to bespoke design environments, as described in the aforementioned design and requirements elucidation methodologies, OTS acquisitions are constrained by their technical solutions. That is, once the functions (capability goals) are defined, solutions are determined by searching through OTS offerings with the intent to find one that best satisfies the capability needs [19]. While the benefits of OTS are minimising cost and schedule risk, since the chosen design is 'mature', it inherently means acceptance of a ship design that has been optimised for someone else's[2] requirements. Hence, an OTS solution is the result of a requirement trade-off process. Morris and Thethy [18] demonstrated how the MBSE approach could be used to inform requirement trade-off

[2] The term 'someone else' is commonly used in an informal manner to encompass Defence Departments, Defence Industry or Naval Design Communities that are external to the ADOD.

decisions and ensure the chosen OTS design is best suited for the RAN's capability needs. The MBSE approach comprises of requirements, functional, physical, analysis and operational behaviour domains into a single design environment. This design environment is used to inform capability stakeholders of the relationship between requirements and the physical design of the system in a similar manner to Brown and Thomas [12]. Within the analysis domain, a Concepts and Requirements Exploration (C&RE) methodology facilitates the development of these relationships. Keystone to the C&RE methodology, and therefore the MBSE approach, is an M&S framework responsible for the generation and exploration of the design space.

Dwyer and Morris [20] built upon this MBSE approach of Morris [16] and Morris and Thethy [18] by improving the fidelity of the original M&S framework. The improvement employed commercial modelling software capable of integrating external applications and simulations tools to allow the generation and exploration of a design space. The result was a comprehensive, flexible and robust Ship Performance M&S framework. The M&S framework was tested by application to the introduction of a new capability into service within the ADOD. The M&S framework was used to generate and allow exploration of a design space to inform capability acquisition stakeholders of requirements definition decisions during the *Risk Mitigation and Requirement Setting* phase of the ADOD CLC. The proposed Ship Performance M&S framework shows promise, when incorporated as part of the MBSE methodology, as being capable of supporting the development of robust, contestable requirements for a naval vessel. In an ADOD context, the proposed M&S framework is well suited for a low resource environment in that it utilises commercial software. Additionally, since the modelling software allows most external applications or simulation tools to be integrated within a single framework, this ensures that a wide range of system attributes can be analysed within the applicable bounds of validity for each tool. Furthermore, due to the inherent flexibility of the modelling software, the Ship Performance M&S framework can be tailored and adapted depending on the design and requirements elucidation activities needed to be performed. As a result, the M&S framework conforms to the structured and systematic approach required of a complex naval design process. In doing so, the M&S framework is capable of building knowledge to support capability stakeholders making design decisions and trade-offs throughout the entire ADOD CLC.

1.2 Modelling and Simulation in a Design Environment

Modelling and Simulation (M&S) methods for use in the design of engineering systems has evolved alongside advances in computer-based technology [21]. These methods enable the designer to test whether design specifications have been met by using virtual rather than physical experiments [22]. Sinha, Paredis [22] state two key benefits of M&S are: "it significantly shortens the design cycle and reduces the cost of design"; "it provides the designer with immediate feedback on design decisions which, in turn, promises a more comprehensive exploration of design alternatives and a better performing final design". In the US DoD acquisition environment Sanders [23] endorsed "Simulation Based Acquisition" as a means to becoming a smart buyer. Where, the improvements in cost, productivity, and quality/performance of the program due to M&S contribute to realising the smart buyer approach.

M&S methods are routinely employed to perform early stage design activities as part of a wider Systems Engineering (SE) approach to the development of complex systems. Sanders [23], states that a principle component to "Simulation Based Acquisition" is an advanced SE environment that supports "sound business practices and common-sense decision making". Supporting the use of M&S to aid decision making in a SE approach, Aughenbaugh and Paredis [24] described how M&S can "help estimate the attributes[3] that would result from a particular decision". Morris, Cook [19] have acknowledged the benefits of integrating M&S and MBSE to assist Concepts and Requirements Exploration (C&RE) of naval ships in an OTS environment, as previously described in Section 1.1. Morris, Cook [19] claim MBSE "facilitates traceability to the strategic intent of the capability" while M&S can "provide evidence to aid defensible decision making". Based on these arguments for the design of a complex system, such as a naval vessel, the benefits of employing M&S are exemplified when integrated with any systems engineering approach for development of complex systems.

The aforementioned benefits of M&S have been associated with only the conceptual stage of design, which are those design and requirements elucidation activities performed prior to acquisition. However, the authors recognise that in an ADOD context the same benefits can come from using M&S to support design decisions throughout the entire CLC [5], as alluded to in Section 1. Therefore, the benefits of M&S in a design environment can contribute to realisation of the ADOD becoming not only a smart buyer, but also a smart owner.

[3] In relation to the design of a system, the estimated attributes are those of that system.

2. Development of the Modelling and Simulation Framework

The commercial software package ModelCenter (Version 12.0) provides a key tool for the development of the Ship Performance Modelling and Simulation (M&S) framework. ModelCenter has two key functions which are pivotal to achieving a complex naval ship design process: integration and exploration.

With respect to integration, ModelCenter provides users with tools and methods enabling them to automate the execution of almost any modelling and simulation application [25]. After automation of applications within ModelCenter's modelling environment, applications and tools can be integrated together allowing the transfer of data to create a simulation workflow. That is, the output values of one application become the input values for another. A key advantage of ModelCenter that the authors have identified is that once a particular application has been integrated, simulation workflows can be rapidly configured to perform specific analyses within the bounds of all integrated tools.

In terms of exploration, ModelCenter allows users to explore and understand the design space by running algorithms and trade study tools on simulation workflows [25]. The exploration functionality supports design synthesis, which enables users to compare and quantify design alternatives based on multiple objectives. In the same process, the user can also identify the sensitivity of, and relationship between significant variables to aid trade-off decisions. Through incorporation of the integration and exploration functionalities, the development of the Ship Performance M&S framework within ModelCenter conforms to the requirements of a complex requirements elucidation methodology.

2.1 Model Library

A repository of models has been created to support a flexible M&S framework that can be efficiently tailored to perform specific design activities to aid design decisions throughout each phase of the CLC. For the proposed Ship Performance M&S framework the authors describe a model as a simulation of a specific naval ship task. In the context of the ModelCenter environment a model is therefore the integration of automated applications and tools set out to perform that specific task. Analysing ship performance in a comprehensive manner requires the library to comprise models relating to naval architecture and naval mission performance assessment. For this reason the model library is categorised by the following ship system characteristics:

- Hullform and Geometry
- Resistance
- Propulsion
- Seakeeping
- Stability

- Weight
- Volume
- Electrical/Power[4]
- Structural Strength
- Combat Systems
- Command, Control, Communication, Computers and Intelligence (C4I) Systems
- Support Systems (non-major system Fundamental Inputs to Capability [FIC])

Models created to simulate specific naval ship tasks of a certain system characteristic are appropriately located within the respective category. Building the model library in such a manner allows the user to efficiently integrate appropriate models depending on the M&S activities that need to be performed. Furthermore, it also supports a collaborative environment where the library can grow and models can be easily identified. The process of tailoring the M&S framework for implementation throughout each phase of the CLC will be demonstrated throughout the remaining sections of the report.

2.2 Evaluating Ship Performance

The previous section introduced system characteristics considered critical for the comprehensive evaluation of ship performance. The aim of this section is to provide more detail of the role each system characteristic plays in the evaluation process. The following details the current status of the model library, which due to creation/adaptation/maturation of models is subject to change.

2.2.1 Hullform and Geometry

With respect to the Ship Performance M&S framework, a common step throughout each of the design activities is for the designer to define the vessel's hullform and geometry. This is because most other ship system characteristic models require the definition of the hullform and geometry prior to execution. As part of the hullform and geometry system characteristic, the Hull Generation Model (HGM) was developed to generate a 3D model of a hullform based on a number of design parameters. Rhinoceros Version 5.0, along with an Orca3D plugin, was employed as the 3D modelling application [26]. Orca3D contains a unique set of design parameters which give the designer control over the hull's overall dimensions, form and bow and transom geometry [27], see Appendix A. Depending on the type of design activity the HGM can be used for design synthesis by setting a range of design parameters, or to generate the hullform of a single design by setting particular design parameters.

[4] Models for these ship system characteristics have not yet been developed and so are not included in Section 2.2. It must be noted that models representative of these characteristics are currently in development or are a part of future work.

2.2.2 Resistance

The resistance characteristic comprises a single model that estimates each hullform's total resistance. Where, the total resistance includes the summation of calm water and added resistance due to waves. Calm water resistance is based on the prediction method originally introduced by Holtrop and Mennen [28]. Calm water resistance can be determined over the entire speed profile. The added resistance in waves prediction is calculated within SHIPMO7 seakeeping code (introduced in Section 2.2.4) using the near-field method proposed by Faltinsen [29]. Reference [30] details the implementation of this method into SHIPMO7 and provides validation results. Within SHIPMO7, added resistance can be determined for a range of speeds, headings and wave characteristics. Results from the resistance model can be used to explicitly evaluate resistance based performance and/or used as a predecessor to the installed power model by supplying necessary resistance data. Resistance prediction is currently limited to monohull hullforms with length-to-beam ratios greater than four and at moderate ship speeds up to Froude Numbers less than 0.4 [31]. However, these limits are applicable to a majority of existing naval vessel designs.

2.2.3 Propulsion

The propulsion system characteristic contains a model used to predict the required installed power. Installed power is calculated over the entire speed profile of the ship, in a range of sea states and relative wave headings. This allows an engine to be sized for the power requirements at the ships maximum speed in the required operational sea-states. The prediction is based on that outlined by Molland, Turnock [32: p. 9-10]. Due to the lack of design data during the early stages of the Risk Mitigation and Requirement Setting phase the prediction method contains a number of assumptions. However, as more design data becomes available throughout the later stages of the CLC, assumptions are replaced with physical data and the accuracy of the prediction method improves.

Subsequent to predicting the installed power requirements of the ship, a model has been developed to appropriately select an exemplar engine configuration. The purpose of this was to allow suitable estimation of fuel consumption and engine dimensions. Of which, such estimations are necessary for other ship system characteristics including stability, weight and volume. Alternatively, this information can be used as a basis for performance evaluation. A database of engine specifications over a large range of power ratings was built from open source data. This database provides the foundation of information governing engine configuration selection. The model uses the installed power value and the preferred engine configuration type (Diesel or Diesel-Electric) as inputs. The model matches engines, based on their rated power output, from the database into a number of possible different configurations, suitable for the configuration type, that satisfy the required installed power. The analyst has control over either direct mechanical or diesel electric configurations. Finally, based on the analyst's preference, an engine configuration is selected to meet either optimal fuel consumption or space/weight requirements.

2.2.4 Seakeeping

As introduced in Section 2.2.2 the seakeeping attribute uses the SHIPMO7 seakeeping code as its foundation for a prediction of the ships seakeeping performance. SHIPMO7 is a strip theory program for computing ship motions and sea loads in regular and irregular seas [31]. Additionally, the program also provides derived responses including local accelerations, slamming, deck wetness and motion-induced-interruptions. Of particular use, the program allows the user to compute these ship motions and derived responses at certain locations for a range of speeds, headings and wave environments. SHIPMO7 seakeeping results are then used to evaluate the ship's seakeeping performance through seakeeping operability indices. The practical benefit of using operability indices is that the resultant value represents the percentage of time a ship is able to remain fully operational performing certain operational activities under specified operating conditions [33]. Within the seakeeping operability model the SHIPMO7 results are collated then combined into a single operability indices equation as per Equation (1).

$$Overall\ Operability = \sum[P(speed\ i) \times P(heading\ j) \times W(criteria\ k) \times Operability(criteria\ k)] \tag{1}$$

Where:

P(x) represents the probability of speed i, or relative heading j

W(x) represents the weighting (relative importance) assigned to each criteria 'k'

Operability(x) represents the operability index (evaluated between 0-1) of each criteria 'k'

From Equation 1 the user is able to define the operational activities, such as seaboat launch and recovery and vessel transit, for assessment by specifying relevant criteria along with a weighting factor that defines the relative importance of each criteria. Likewise, the user defines the operating conditions for assessment by specifying speed and relative wave heading profiles that include the likelihood of each condition occurring. The seakeeping operability model is limited by its ability to also capture results over a range of wave conditions. Therefore, the *Overall Operability* measure must be determined for a specific wave height and period. This wave height and period can be the average of the conditions likely to be expected over a mission, or a series of discrete conditions that a vessel may encounter over the duration of a mission.

2.2.5 Stability

The stability characteristic considers both intact and damage stability related ship performance. To achieve this, a stability model that utilises MAXSURF Stability software was created [34]. The outcome of the model is to generate a limiting KG curve. Where, KG is the height of a vessel's centre of gravity above its keel. A limiting KG curve represents the highest KG verses displacement that a ship can obtain and still comply with stability criteria [35]. Therefore, the limiting KG curve can be used for appropriate evaluation of a ships stability performance since it is a single measure that considers both intact and damage scenarios. To generate the limiting KG curve the model requires definition of the hull and all watertight compartments. Criteria used for compliance comes from

DEF (AUST) 5000 [35] and includes General righting arm (GZ) criteria and Damage Stability criteria. The model calculates the limiting KG value over a set range of displacements for the intact case and a number of damage cases. The total number of damage cases represents each possible case where a specified percentage of the waterline is damaged over the entire length of the ship, ensuring coverage of all possible damage scenarios. Finally, the minimum KG over all cases is determined for each displacement to produce the limiting KG curve.

2.2.6 Weight

The weight characteristic focuses mainly on estimating the lightship mass of the ship. A simple weight estimate model is based on parametrically derived equations for estimating the total ship displacement. The method is that outlined by Parsons [36: ch. 11], where the total displacement in tonnes is the combination of Dead-Weight (DWT) and lightship weight. Estimating the lightship weight is valuable since it is required as an input for the stability model. Similarly, estimating the DWT provides the designer with an insight to the likely tank sizings, provisions and number of crew required for the ship. In turn, these factors must be considered in the evaluation of stability and endurance performance.

2.3 Modelling Environment

With the establishment of the model library, integrating chosen models together within ModelCenter's modelling environment to form a simulation workflow forms the next step in the proposed Ship Performance M&S framework. During this step, the designer can select then integrate a particular model depending on the analysis needed to be performed.

After forming the simulation workflow the next step in the Ship Performance M&S framework is generating then exploring the design space. In the modelling environment, this is achieved through the application of a number of trade study tools. Simply, trade study tools allow the purposeful changing of input variables in a model to observe the corresponding changes in outputs [25]. More specifically, these tools utilise Design of Experiments (DOE) techniques. During this process, a design space is generated that provides the designer with an understanding of relationships between design variables. Through exploration of these relationships the designer is then able to make informed design decisions for the proposed study. This concludes as the last step in the Ship Performance M&S framework.

The remainder of this report, and the following series of reports details how the Ship Performance M&S framework can be implemented at each phase of the CLC. This includes a description of the analysis, development of a tailored simulation workflow to achieve the outcomes of each proposed study, and finally the generation and exploration processes of the design space to support informed trade-off decisions.

3. Risk Mitigation and Requirement Setting

This phase of the ADOD CLC involves the development and progression of capability options through an aligned investment approval process. The outcome of this phase will transition the project into a government approval milestone to proceed into and commence the *Acquisition* phase. The primary output of this phase is a firm contractible proposition to acquire and sustain the required capability [5].

In the context of the RAN, the required capability will be either submarines or surface ships, typically acquired using OTS strategies. Implementing and executing the Ship Performance M&S framework during this phase can assist the development and progression of the capability through assisting the development of requirements. The M&S framework can be used to perform preliminary design and requirement elucidation activities that support an improved understanding and more thorough definition of the requirements that are representative of the OTS naval vessel marketplace. In the SE discipline there is a growing understanding that the process of requirements setting should include preliminary design activities [20]. Supporting this claim Crowder, Carbone [37] states “The activities which we would call design are nothing different from the activities required to create the ‘To-be’ requirements”. In an OTS environment, performing preliminary design activities ensures that the requirements released to industry (the primary output of this phase), in the form of technical specifications, constrains the technical solutions offered by designers to those that will adequately meet the capability need, contributing towards Defence becoming a smart buyer [20].

3.1 New Hydrographic Survey Capability Case Study

The case study for the *Risk Mitigation and Requirement Setting* phase involves the acquisition of an indicative hydrographic survey capability into the RAN. The study is based on an exemplar capability need that employs a ship based solution in combination with an array of uncrewed[5] systems tasked to perform the survey functions. The aim of the study was to analyse the impact of vessel type and hullform design for the suitability to meet an optimal hydrographic survey capability. For the case study, the Ship Performance M&S framework was used in conjunction with the MBSE methodology outlined by Morris and Thethy [18] to facilitate the generation of a realistic design space detailing the relationships between hullform design and ship performance. Next, the framework was used to explore the design space. Aligning the MBSE methodology with the exploration process could assist capability acquisition stakeholders make informed design decisions throughout the requirements definition process.

[5] Uncrewed is synonymous with the commonly known term ‘unmanned’. In the context of this report, an uncrewed system is absent of on-board crew or personnel.

3.2 Implementing the Modelling and Simulation Framework for Risk Mitigation and Requirement Setting Phase Support

This section of the report outlines the process of how the Ship Performance M&S framework is implemented to achieve the required outcomes of the proposed study. This includes the process of integrating SE practices to help tailor an appropriate simulation workflow.

3.2.1 Establish the Mission Scenario

This first step in implementing the proposed M&S framework involves defining the mission scenarios the naval capability is required to undertake. The mission scenarios comprise operational activities, which can be identified from an Operational Concept Document (OCD), or consulting with Subject Matter Experts (SMEs) if the OCD is unavailable.

A part of capturing all capability needs in the mission scenario is addressing the likely operating environments the system will experience. This is especially important for the naval ship design process, since the design of a ship, especially considering ship type, is influenced by the environment it is to operate in throughout its lifespan. The operating environment is reflected throughout the execution of the M&S framework in the form of input parameters required for some models, for example: defining the wave conditions in the seakeeping operability model, see Section 2.2.4. For a hydrographic survey capability, it was proposed that the ship would operate in waters off the north eastern coastline of Australia.

Capturing the activities and operating environment in the mission scenario for the hydrographic survey capability case study was done with SMEs using an indicative mission where the ship transited from a base located on the north east coastline of Australia to an offshore operational area. Once in the operational area uncrewed systems would be launched to conduct hydrographic and oceanographic survey activities while the ship loiters in the operational area to collect and process the survey data. After completion of the survey activities the systems would be recovered prior to the ship transiting back to base.

3.2.2 Establish Key Performance Parameters

Key Performance Parameters (KPPs) were established from the operational activities described in the mission scenario from the previous section. In the US DoD context a KPP is considered a "performance attribute of a system considered critical or essential to the development of an effective military capability" [38].

Three KPPs related to the performance of the ship were established; two based on the seakeeping attributes of the ship and one based on the vessel's total resistance at its transit speed. Opposed to other KPPs which could have been selected such as stability, structural strength etc. these three KPPs reflect characteristics which are considered critical by SME's for a HSV to exhibit adequate performance for the operational concept. From Section 2.2.4

both seakeeping KPPs were in the form of seakeeping operability indices. Referring to the seakeeping operability model two seakeeping operability indices were created to reflect the ships seakeeping performance while performing transiting and L&R activities respectively. From Section 2.2.2 the total resistance at transit speed based KPP was in the form of a total resistance per tonne displacement (R_T/Δ) measure. Referring to the capability of the resistance model, the R_T/Δ measure over the speed profile of the vessel was created by dividing the total resistance in a specified wave environment by the vessel's respective displacement. For a more detailed breakdown of the KPPs see Appendix B.

3.2.3 Establish the Simulation Workflow

After establishing the KPPs the relevant models can be integrated together in the modelling environment of the M&S framework to form the simulation workflow of the new hydrographic survey capability study.

Outlined previously in Section 3.1, the aim of the study was to analyse the impact of vessel type and hullform design for the suitability to meet an optimal hydrographic survey capability. To achieve this, the Hull Generation Model formed the basis of the simulation workflow. Next, the seakeeping operability model was integrated allowing the seakeeping based KPPs to be analysed for each hullform generated. Finally, the resistance model was integrated to allow for the calculation of the resistance based KPP. Figure 2 illustrates the integration process and the final simulation workflow.

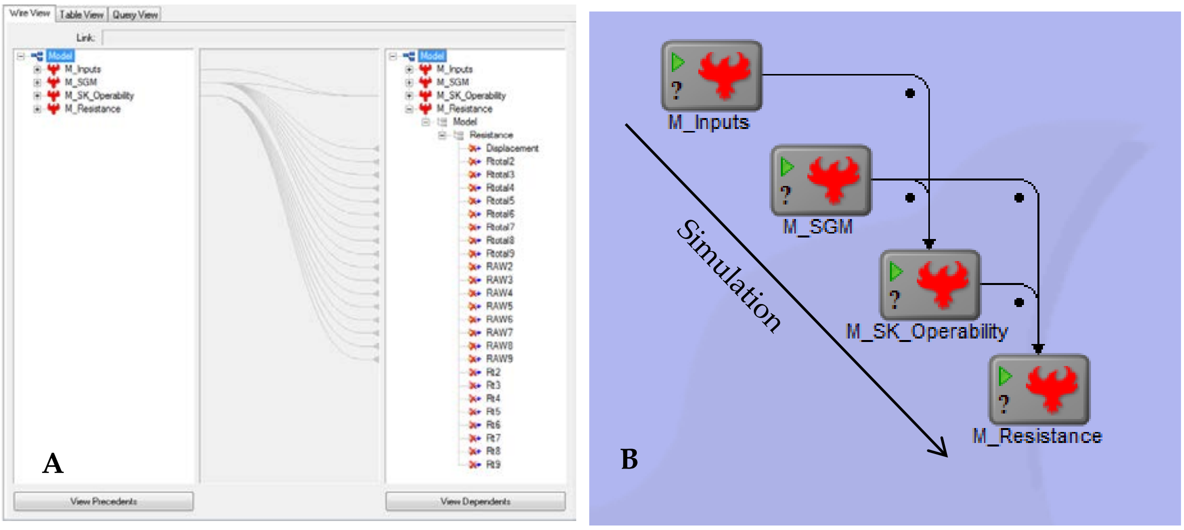

Figure 2 (A) Linkages between models allowing the transfer of data between inputs and outputs of separate models; (B) Simulation workflow – simplified view of integrated models

3.2.4 Aligning the M&S framework with the MBSE Methodology

As previously mentioned in Section 3.1, the M&S framework was used in conjunction with an MBSE methodology enabling traceability between design space exploration and the capability need. Figure 3 illustrates this traceability through the decomposition of the

KPPs from the indicative hydrographic capability need. Referring to Figure 3 it is shown how the need to conduct "Hydrographic and Oceanographic Data Collection" is decomposed respectively into operational activities, operational needs, system functions then KPPs. In this manner, the design space exploration process facilitated by the M&S framework allows capability acquisition stakeholders to trace design decisions through to the capability need. Hence, stakeholders will be able to clearly demonstrate the relationship between design decisions and the requirements, supporting the requirements definition process.

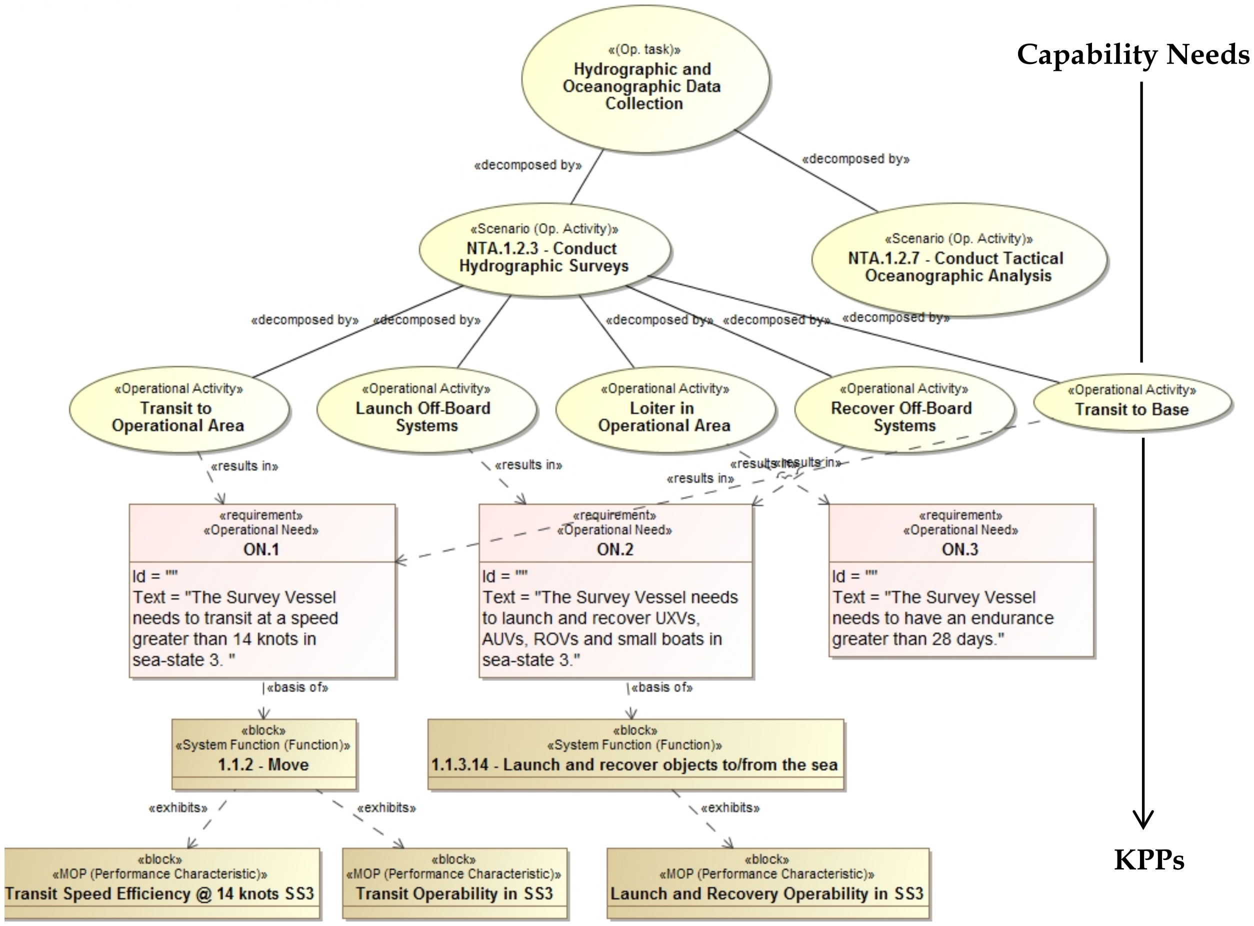

Figure 3. Functional breakdown diagram describing the traceability process between the KPPs (the bottom most level) and the capability need (the upper most level)

3.2.5 Executing the Simulation Workflow

Executing the simulation workflow initiates the generation of a design space, the first step of the exploration process. Previously introduced in Section 1.1 generation and exploration of the design space is through application of trade study tools. For the case study, ModelCenter's Design of Experiments tool was used [25]. Design of Experiments (DOE) is a method consisting of purposeful changes of the inputs to a process in order to observe the corresponding changes in the outputs [39]. Where, the inputs are hull design variables and the outputs are KPPs.

Prior to running the DOE tool the boundaries of the design space were first defined to ensure realistic solutions comprise the design space. To achieve this, margins were applied to input parameters required for the DOE tool. The sizes of these margins were based on subject matter expertise and engineering judgement, the result was a ± 15% margin applied to all hull design variables.

The above process was repeated three times in order to analyse the suitability of a Hydrographic Survey Vessel (HSV), Offshore Patrol Vessel (OPV) and frigate vessel types for the hydrographic survey capability mission. This analysis will support the identification of the most suitable hullform for the mission scenario identified in the previous step. The hull design variables used to generate each design space were representative of generic hullforms typical of each vessel type. Table 1 details the upper and lower limits for each hull design variable used to create the design space for each vessel type. Hull design variables were distinguished into two categories: global hull design variables, and local hull design variables. Global hull design variables are those design variables that govern the dimensions of the vessel and include *Length, Length to Beam ratio (L/B), Beam to Draft ratio (B/T) and Depth*. Local hull design variables control the form and confined geometric aspects of the hull; they include the remainder of hull design variables from Table 1.

Table 1. Boundaries of the design space for each vessel type represented by upper and lower limits of hull design parameters

Design Variable	**HSV**		**Generic OPV**		**Generic Frigate**	
	Low	**High**	**Low**	**High**	**Low**	**High**
Length (m)	70	95	70	95	70	95
L/B	4.05	5.15	5.48	6.58	5.98	7.08
B/T	3.27	3.97	2.96	3.66	3.88	4.59
Depth (m)	8.65	10.55	9.01	10.91	7.94	9.85
Max Area Location	0.35	0.65	0.35	0.65	0.30	0.60
Prismatic Control	0.27	0.57	0.35	0.65	0.10	0.40
Section Tightness Aft	0.45	0.75	0.85	1.00	0.35	0.65
Section Tightness Fwd	0.65	0.95	0.65	0.95	0.52	0.82
Section Tightness Mid	0.35	0.65	0.75	1.00	0.67	0.97
Deadrise Aft	0.55	0.85	0.15	0.45	0.00	0.00
Deadrise Fwd	0.25	0.55	0.75	1.00	0.75	1.00
Deadrise Mid	0.00	0.20	0.15	0.45	0.00	0.27

Side Slope Fwd	0.65	0.95	0.55	0.85	0.00	0.00
Side Slope Aft	0.00	0.25	0.00	0.25	0.05	0.35
Flare Fwd	0.65	0.95	0.35	0.65	0.75	1.00
Stem Rake (deg)	19.55	28.45	30.55	39.45	25.55	34.45
Stem Curvature	0.15	0.45	0.00	0.20	0.00	0.00
Bow Rounding	0.00	0.30	0.00	0.30	0.00	0.25
Forefoot Shape	0.15	0.45	0.35	0.65	0.00	0.00
Transom Rake (deg)	-14.95	-11.05	0.00	0.00	0.00	0.00
Transom Deck Width	0.75	1.00	0.70	1.00	0.73	1.00
Keel Rise Pt	0.55	0.85	0.38	0.68	0.23	0.53
Keel Rise Rate Aft	0.16	0.46	0.37	0.67	0.25	0.55
Keel Rise Rate Fwd	0.04	0.34	0.00	0.24	0.00	0.00

3.3 Results and Discussion

The design space for each vessel type was generated by running a 1000 run DOE. To efficiently construct the design space Orthogonal Arrays (OAs) were used for the experimental designs due to their space filling properties; ensuring design points are effectively infiltrating the design space.

After generation of the design space for each vessel type, design space exploration tools were employed to gain an improved understanding of the relationships between vessel type and hull design variables on ship performance with respect to the HS capability outlined in 3.2.1.

The discussion of results was divided into two sections. The first section is based on comparing the design spaces of each vessel type against meeting an optimal hydrographic survey capability, see Section 3.3.1. Conducting the vessel type comparison first is important since there is potentially a number of hullforms that could meet the hydrographic survey capability needs. This design activity can determine the most suitable vessel type and support stakeholder decision-making about setting vessel requirements. The second section is based on determining the individual hull design variables that contribute towards an optimal hydrographic survey capability based on the most suitable vessel type determined from the vessel type comparison, see Section 3.3.2. Determining the relationship between design parameters and ship performance helps to aid defensible design decisions during requirements setting activities. An understanding of these relationships supports the definition of requirements, and therefore the development of a technical specification that represent an optimised capability.

3.3.1 Vessel Type Comparison

Seakeeping and resistance based KPPs were determined for each vessel for a number of sea states. The top of sea states 3, 4 and 5 were used for representation of the wave conditions throughout the simulation workflows. The corresponding wave heights and wave periods used for each sea state were taken from DEF (AUST) 5000 [33] and are detailed in Table 2. Between these sea states a majority of wave conditions are captured, as detailed by BMT [40], for the ocean environment described in the mission scenario, see Section 3.2.1. Furthermore, simulating multiple sequential wave conditions allows for direct analysis of the influence of increasing sea state on the KPPs, as well as a general understanding of each vessel types performance over a range of operational conditions.

Table 2. Respective wave heights and wave periods for each sea state

Top of Sea State	Wave Height (m)	Wave Period (s)
3	1.25	6.8
4	2.5	7.9
5	4	8.7

For a thorough comparison of each vessel type's performance, 2D scatter plots of the design space were developed to demonstrate the relationship between both seakeeping operability KPPs (L&R (Launch and Recovery) operability and transit operability) and the total resistance per tonne displacement (R_T/Δ) KPP at 14 knots. 14 knots was chosen for this analysis as it represents typical transiting speeds of the ADOD's current HS capability. Employing 2D scatter plots design points can be analysed as part of the entire design space, the optimal region of the design space, or individually. For each 2D scatter plot the Y-axis represents the L&R operability and the X-axis represents the R_T/Δ at 14 knots of each design point. Furthermore, the colour scale of each plot illustrates the Transit Operability of each design point. For the following analyses, when assessing the most optimal region of the design space only the L&R operability and R_T/Δ KPPs are discussed since the pareto-front is representative of design points optimised with respect to only these two KPPs. For each respective sea state, the 2D scatter plots are scaled appropriately for direct comparison of each vessel type.

Assisting the comparison of vessel types, histogram plots were used to gain a statistical understanding of the entire design space to best summarise and compare the overall performance of each vessel type. Histograms were used to determine the mean and standard deviation values for each vessel type's entire design space, providing an insight into the most common performance characteristics as well as the distribution of performance levels for each vessel type.

For a detailed analysis and comparison of vessel types that demonstrates how the M&S framework can be used to support informed, smart decision making during the Risk Mitigation and Requirement Setting phase of the ADOD CLC, the following discussion covers the analysis for a sea state 3 (SS3) wave environment. SS3 was used because it is the most commonly occurring wave condition experienced for the ocean area described in Section 3.2.1 [40].

3.3.1.1 Vessel Type Comparison in Sea State 3

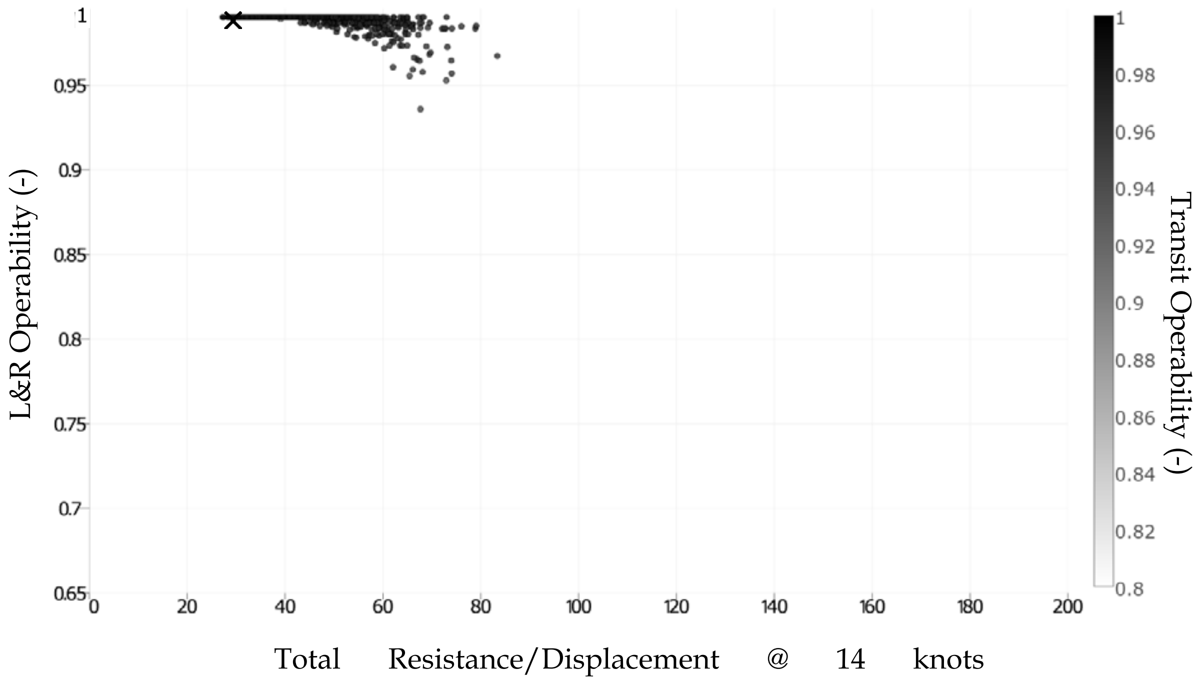

Figure 4. Scatter plot of the hydrographic survey vessel type hullform design space in SS3 illustrating the relationship between L&R operability and Total Resistance per tonne Displacement at 14 knots. Colour gradient represents the respective Transit operability.

The design space of the HSV type hullform in SS3 can be seen in Figure 4. Analysing the 2D scatter plot, it is clear that a majority of the design points exhibited maximum L&R operability and a high transit operability. That is, for SS3 a large region of the HSVs design space is able to achieve 100% operability for L&R and transiting activities. Considering the ranges of performance, design points ranged from 94% to 100% for L&R operability. Likewise, for transit operability design points were spread over a range of performance from 88% to 100%.

Analysing the histogram results for L&R and transit operability performance supports the analysis of the scatter plot in the previous paragraph. Figure 5A shows the mean L&R operability was 99% with a considerably small standard deviation of 0.44%. Figure 5B shows the mean transit operability was 98%, also with a considerably small standard deviation of 0.96%. These results indicate that the HSV type performs considerably well in SS3 while conducting seakeeping based L&R and transiting activities.

From Figure 4, all design points experienced a moderate spread for R_T/Δ ranging from 25 to 75 kN/Tonne. Analysing the results of the histogram for R_T/Δ from Figure 5C, the mean performance of all design points was 44.9 kN/Tonne with a standard deviation of 10.3 kN/Tonne. The mean of the population is nearer the best performing design points, and the standard deviation is moderate. Therefore, the HSV type exhibits good resistance performance in SS3.

The most optimal region of the design space, the pareto-front illustrated in Figure 4 (represented by the black cross), comprises of a single design point, Design 773HS. The performance of 773HS is detailed in Table 3 (later in this section).

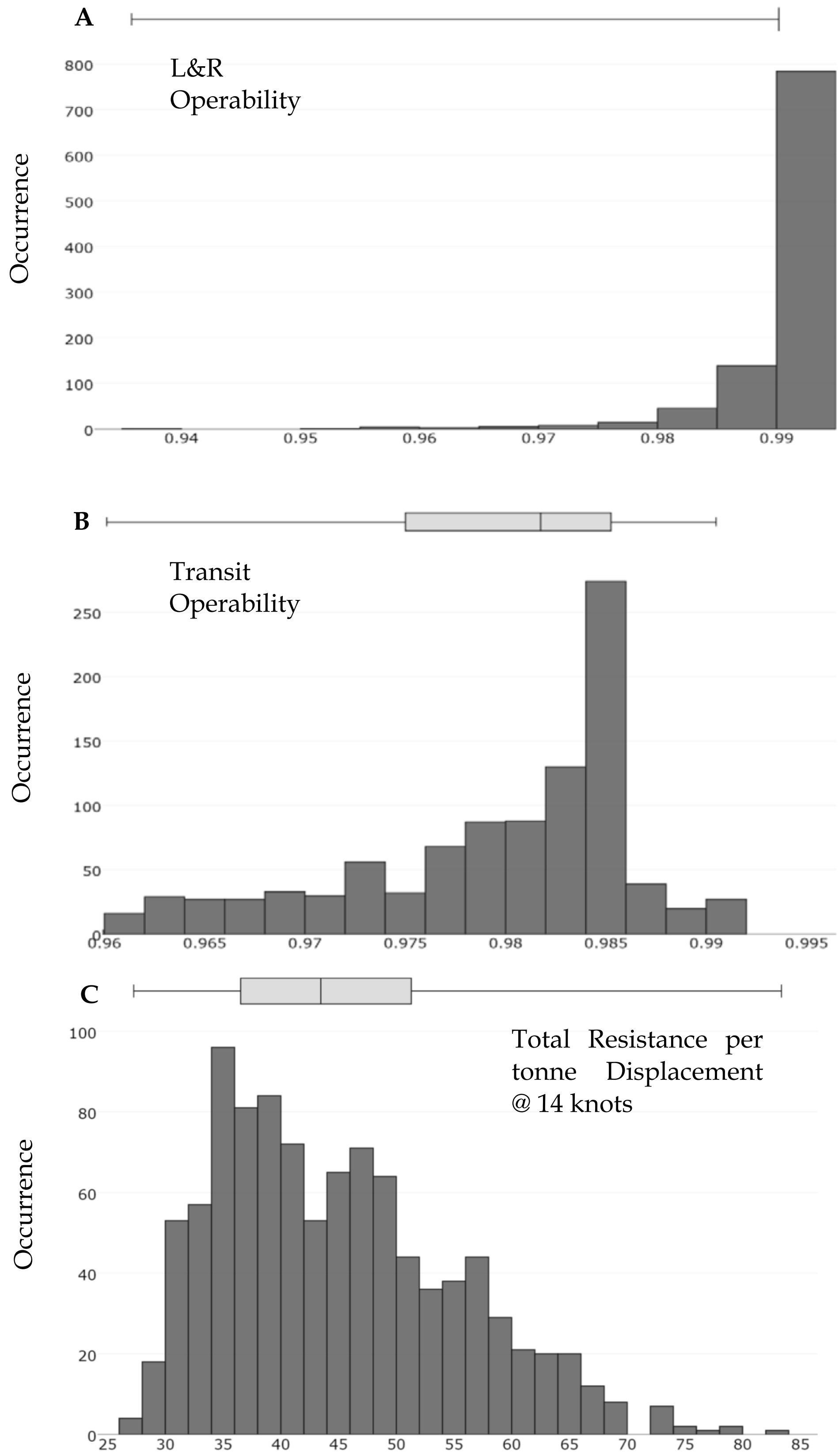

Figure 5. Histogram plots of the hydrographic survey vessel type hullform in SS3 for: (A) L&R operability; (B) Transit operability; (C) Total Resistance per tonne Displacement at 14 knots

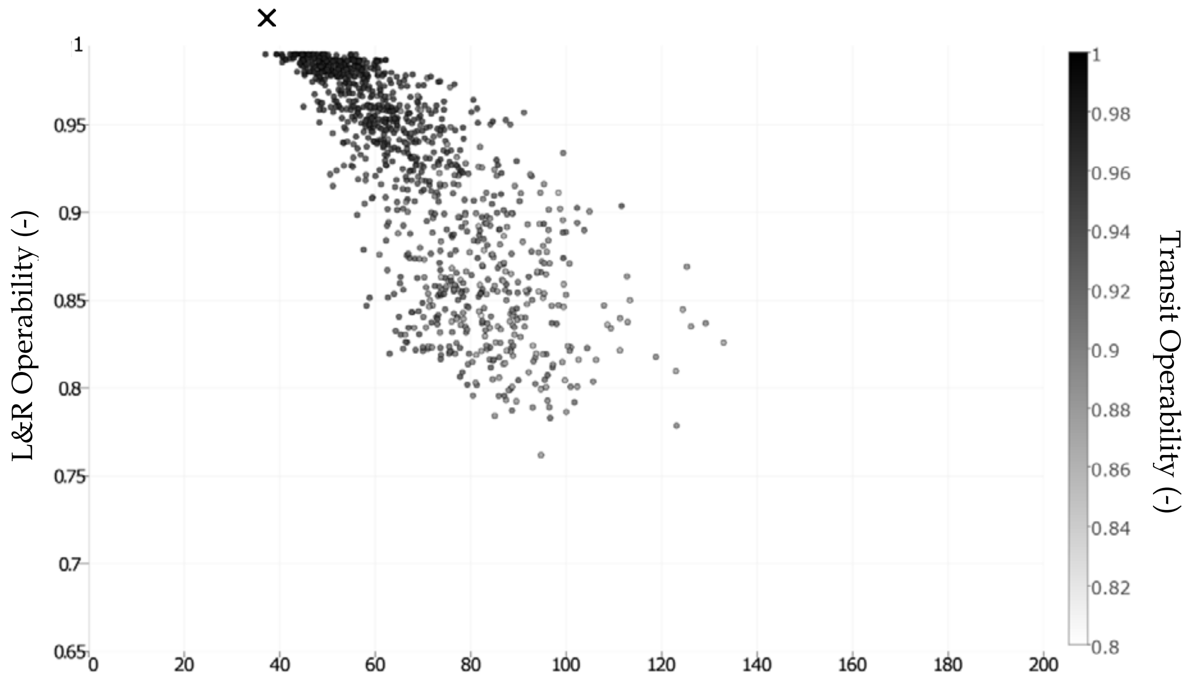

Figure 6. Scatter plot of the offshore patrol vessel type hullform design space in SS3 illustrating the relationship between L&R operability and Total Resistance per tonne Displacement at 14 knots. Colour gradient represents the respective Transit operability.

Figure 6 illustrates the design space of the Offshore Patrol Vessel (OPV) type hullform in SS3. Firstly, comparing the 2D scatter plots of the HSV (Figure 4) and OPV it is clear that both vessel types have dissimilar performance characteristics for the KPPs considered; with the design space of the OPV being considerably larger. Design points of the OPV are spread over a relatively large range for L&R operability, ranging from almost 75% to 100%. Similarly, design points also experienced a marginally larger range of performance for transit operability than the HSV, ranging from 85% to 100%. Therefore, due to a larger range of performance than the HSV, with more design points exhibiting lower L&R and transit operability performance, it is evident that the OPV type is outperformed by the HSV type in SS3. These observations are reaffirmed by analysing the histograms of the OPV type for L&R and transit operability in Figure 7A and Figure 7B respectively.

Figure 7A shows that the mean L&R operability for the OPV hullform was 92%, with a standard deviation of 5.93%. Additionally, Figure 7B shows that the mean OPV hullform transit operability was 94%, with a standard deviation of 2.97%. Comparing the L&R and transit operability histogram results of the OPV hullform to those achieved by the HS hullform there is a reduction in the mean performance of 7% and 4% respectively. Furthermore, there is also an increase in the standard deviation for each operability; increasing by as much as 5% for L&R operability. Given this comparison it is clear that the OPV is outperformed by the HSV for L&R and transit operability in SS3 when considering the entire population of design points.

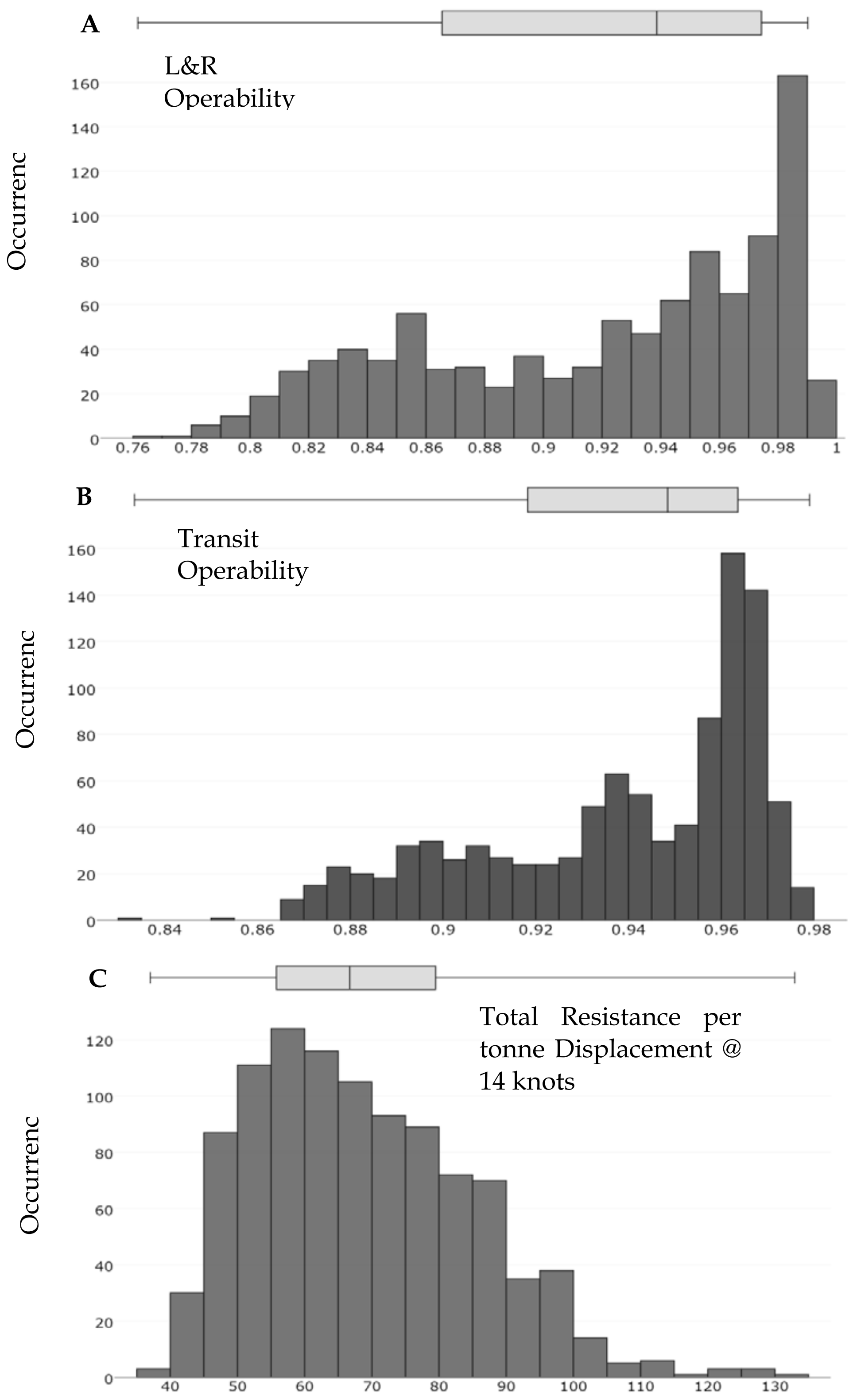

Figure 7. Histogram plots of the offshore patrol vessel type hullform in SS3 for: (A) L&R operability; (B) Transit Operability; (C) Total Resistance per tonne Displacement at 14 knots

Observing the 2D scatter plot from Figure 6 it is evident that the OPV hullform exhibits similar R_T/Δ performance to the HSV with a majority of design points falling within a range of 35 to 100 kN/Tonne. Analysing the histogram results from Figure 7C, the mean R_T/Δ was 68.8 kN/Tonne with a standard deviation of 16.38 kN/Tonne. Comparing the R_T/Δ histogram results to the HSV, the OPV has a 23.9 kN/Tonne greater mean R_T/Δ and a standard deviation that is 6.08 kN/Tonne larger. Therefore, the OPV is outperformed by the HSV for R_T/Δ performance at 14 knots in SS3 when considering the entire generated design space.

Despite a decrease in performance of the OPV hullform relative to the HSV hullform when considering the entire design space of each, from Figure 6 a large portion of design points still exhibit high L&R and transit operabilities and a low R_T/Δ measure. Similar to the HSV the optimal region of the design space is represented by a single design point located on the pareto-front. Highlighted in Figure 6, design 775OPV is the non-dominated design with a maximum L&R operability of 100% and a minimum R_T/Δ measure of 37 kN/Tonne. In comparison to the design 773HS, design 775OPV has only a marginal decrease in performance across all KPPs. Directly comparing design 775OPV to design 773HS, design 775OPV had an equal L&R operability and a greater R_T/Δ measure by approximately 10 kN/Tonne. This indicates that the optimal region of the design space for OPV type hullform exhibits similar performance characteristics to the optimal region of the HSV type hullform, see Table 3. Therefore, considering only design points located in the optimal region of the design space, the OPV type is able to achieve an almost equal performance to the HSV type.

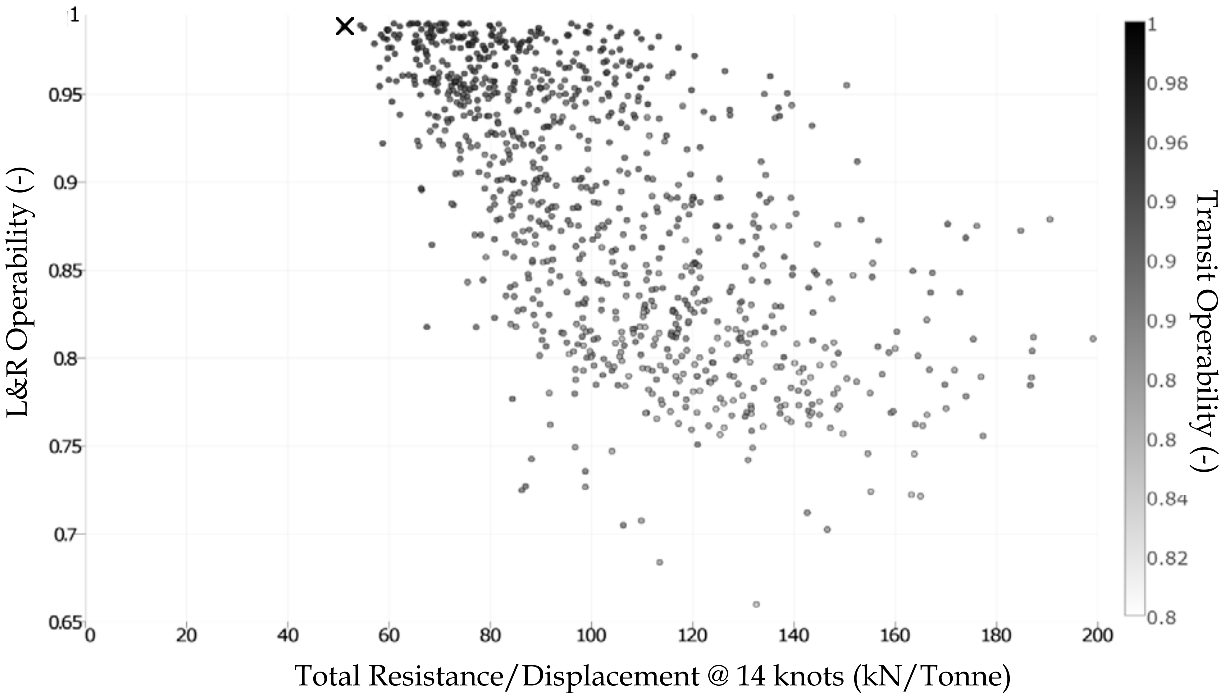

Figure 8. Scatter plot of the frigate type hullform design space in SS3 illustrating the relationship between L&R operability and Total Resistance per tonne Displacement at 14 knots. Colour gradient represents the respective Transit operability.

The design space of the frigate vessel type hullform in SS3 can be seen in Figure 8. In comparison to figure 4 and Figure 6, the design points of the frigate hullform are spread over the largest range of performance for both L&R and transit operability, of all vessel types. Considering all design points, the design space of the frigate ranges over an L&R operability from 65% to 100% and a transit operability from 85% to 100%. However, it is worth noting that the frigate has an equivalent range of performance for transit operability performance to that of the OPV.

A deeper understanding of the frigate type's L&R and transit operability can be gained by analysing histogram plots of the entire population of design points. Figure 9A shows that the mean of the population achieved an L&R operability of 89% with a standard deviation of 7.47%. Furthermore, Figure 9B shows that the mean of the population achieved a transit operability of 92% with a standard deviation of 2.76%. Comparing the L&R and transit operability histogram results to the OPV the mean performance of the frigate is lesser by 3% and 2% respectively. Moreover, the standard deviation of the frigate is 1.5% larger than the OPV for L&R operability, though has a similar standard deviation for transit operability. By comparison to the HSV, the mean L&R and transit operability of the frigate was 10% and 6% less respectively. Additionally, the standard deviations were 7% and 2% larger for L&R and transit operability respectively. These results confirm that, considering the entire population of design points, the frigate type hullform is the worst performing for both L&R and transit operability performance in SS3.

Analysing the 2D scatter plot from Figure 8 it can be seen that the R_T/Δ performance of the frigate type hullform at a transit speed of 14 knots ranges from 50 to 200 kN/Tonne. This indicates that the frigate exhibits the worst R_T/Δ performance of all vessel types. Analysing the histogram results for R_T/Δ in Figure 9C, the mean of the population for the frigate hullform achieved a R_T/Δ of 103.4 kN/Tonne with a standard deviation of 25.56 kN/Tonne. Comparing the R_T/Δ histogram results to both HSV and OPV types the frigate type has a greater mean R_T/Δ by 58.5 kN/Tonne and 34.6 kN/Tonne respectively. The difference between the mean R_T/Δ performances is significant; the frigate experiences on average almost double the overall resistance of the HSV type in SS3. These results provided, the frigate is considerably outperformed by both the OPV and HSV types for R_T/Δ at 14 knots in SS3 when considering the entire population of design points.

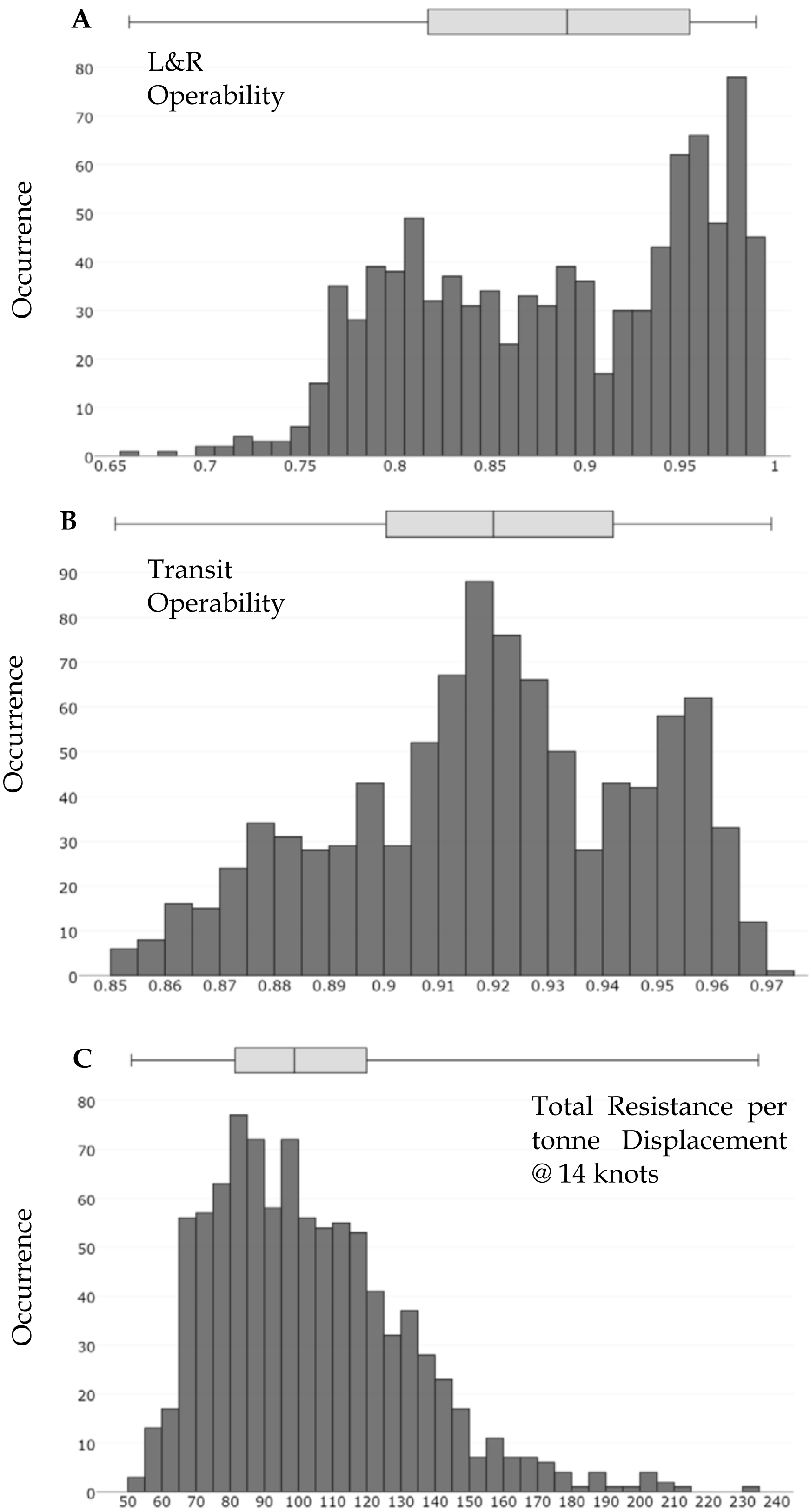

Figure 9. Histogram plots of the frigate vessel hullform in SS3 for: (A) L&R operability; (B) Transit Operability; (C) Total Resistance per tonne Displacement at 14 knots

In comparison to the HSV and OPV type hullforms, a smaller proportion of design points for the frigate occupied the most optimal region of the design space. Analysing the optimal region of the design space supports the notion that the frigate vessel hullform was outperformed by both HSV and OPV type hullforms. Highlighted in Figure 8 as the pareto-front, Design point 775F is the non-dominated design with a maximum L&R operability of 99% and a minimum R_T/Δ measure of 51 kN/Tonne. In comparison to design points 773HS and 775OPV, design point 775F has a marginal decrease in performance for L&R and operability and a substantial decrease in performance for R_T/Δ. Design point 775F has an L&R operability 1% lower compared to design points 773HS and 775OPV. Design point 775F has a R_T/Δ measure that is 24 kN/Tonne more than design point 773HS and 14 kN/Tonne more than design point 775OPV. Based on these findings, considering the most optimal region of the design space, the frigate vessel hullform is outperformed by both HSV and OPV type hullforms, see Table 3. This type of analysis can be repeated for each of the sea states of interest for the hydrographic survey capability to gain an understanding of the relative levels of performance of each of the hullforms. A summary of this comparison is provided in the next section.

Table 3. Summary of the performance of designs from optimal region of the design space for SS3

	Non-Dominated Designs			
	Maximum L&R Operability		**Minimum R_T/Δ @ 14 knots**	
Vessel Type	**Design**	**L&R Operability (-)**	**Design**	**R_T/Δ (kN/Tonne)**
HSV	773HS	1.00	773HS	27.3
OPV	775OPV	1.00	775OPV	37
Frigate	775F	0.99	775F	51

Analysing the summary of results for the most optimal designs for each vessel type hullform from Table 3, when considering the aggregation of both KPPs it is evident that the HSV outperforms both OPV and Frigate types. These results indicate that irrespective of the range of hullform attributes typical to a particular vessel type, there are a set of hullform variables that contribute to optimal performance. Further insight into this finding is needed to understand the feasibility of the optimal region of the design space prior to this information being used to infer design decisions, i.e. do OTS designs for these vessel types actually exist? Section 3.3.2 provides an approach to answer these questions, as well as methods to support deeper understanding of the hull design variables that contribute to improved performance.

3.3.1.2 Vessel Performance Summary for each Sea State

Section 3.3.1.1 discusses the performance of each vessel type in SS3 only. However, seakeeping and resistance results were determined for SS4 and SS5 also. A summary and comparison of the mean performance results between each vessel type can be seen in Tables 4, 5 and 6 for SS3, SS4 and SS5 respectively. Additionally, a comparison of each vessel type's mean and optimal performance for each of the three KPPs with respect to increasing sea state can be seen in Figures 10 and 11 respectively. Results data for mean performance considers the entire population of design points. Conversely, results data for optimal performance considers the non-dominated designs that exhibited maximum performance for the respective KPPs analysed in Figure 11.

Table 4. Summary of the mean performance results in sea state 3

Vessel Types	**Sea State 3**		
	L&R Operability	Transit Operability	R_T/Δ @ 14 knots
HSV	**0.99**	**0.98**	**44.9**
OPV	**0.92**	**0.94**	**68.8**
Relative % Difference (from HSV)	-7.1%	-4.1%	53.2%
Frigate	**0.89**	**0.92**	**103.4**
Relative % Difference (from HSV)	-10.1%	-6.1%	130.3%
Relative % Difference (from OPV)	-3.3%	-2.1%	50.3%

Table 5. Summary of the mean performance results in sea state 4

	Sea State 4					
Vessel Types	L&R Operability	Relative % Difference (from SS3)	Transit Operability	Relative % Difference (from SS3)	R_T/Δ @ 14 knots	Relative % Difference (from SS3)
HSV	**0.94**	-5.1%	**0.92**	-6.1%	**63.9**	42.3%
OPV	**0.75**	-18.5%	**0.84**	-10.6%	**105.3**	53.1%
Relative % Difference (from HSV)	-20.2%		-8.7%		64.8%	
Frigate	**0.73**	-18.0%	**0.83**	-9.8%	**157.4**	52.2%
Relative % Difference (from HSV)	-22.3%		-9.8%		146.3%	
Relative % Difference (from OPV)	-2.7%		-1.2%		49.5%	

Table 6. Summary of the mean performance results in sea state 5

	Sea State 5					
Vessel Types	L&R Operability	Relative % Difference (from SS4)	Transit Operability	Relative % Difference (from SS4)	R_T/Δ @ 14 knots	Relative % Difference (from SS4)
HSV	**0.77**	-18.1%	**0.77**	-16.3%	**105.6**	65.3%
OPV	**0.65**	-13.3%	**0.73**	-13.1%	**181.4**	72.3%
Relative % Difference (from HSV)	-15.6%		-5.2%		71.8%	
Frigate	**0.63**	-13.7%	**0.74**	-10.8%	**272.9**	73.4%
Relative % Difference (from HSV)	-18.2%		-3.9%		158.4%	
Relative % Difference (from OPV)	-3.1%		1.4%		50.4%	

Considering the statistical analysis of the entire design space for each sea state there was a significant improvement in L&R and transit operability performance for the HSV compared to both the OPV and frigate. This gap in performance between either of the vessel types varied with increasing sea states; see Tables 4, 5 and 6. From sea state 3 to 4 the performance degradation of the HSV was significantly less than that of the OPV and frigate. However, this performance degradation trend diverged from sea state 4 to 5; the HSV experienced a greater decline in performance compared to the OPV and frigate. Even though in SS5 the HSV achieved the best L&R and transit operability performance, these results suggest that the L&R and transit seakeeping attributes of the HSV are optimised for a specific range of wave conditions. Conversely, the OPV and frigate hullforms appear to be designed to exhibit an adequate level of L&R and transit operability performance over a broader range of wave conditions. Provided with this information stakeholders are able gain a deeper understanding of the performance trade-offs between vessel types. Furthermore, this information provides traceability between selection of the most suitable vessel type and the capability needs. Establishing the traceability from high-level capability needs to a high-level physical description of the system in such a manner supports defensible and justifiable design decisions. For example, the capability need was for a hydrographic survey vessel to be deployed in north-eastern Australian waters. For the range of wave conditions experienced in this environment (primarily SS3) the HSV outperforms both the OPV and frigate, and so, with justification, would be chosen as the preferred vessel type.

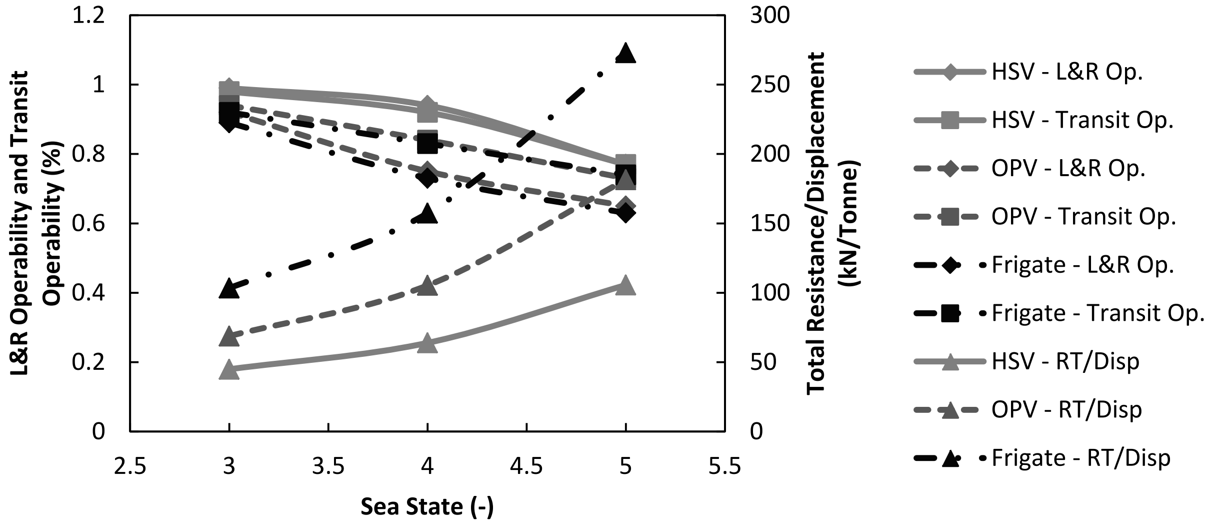

Figure 10. Mean performance of each KPP for each vessel type for increasing sea state

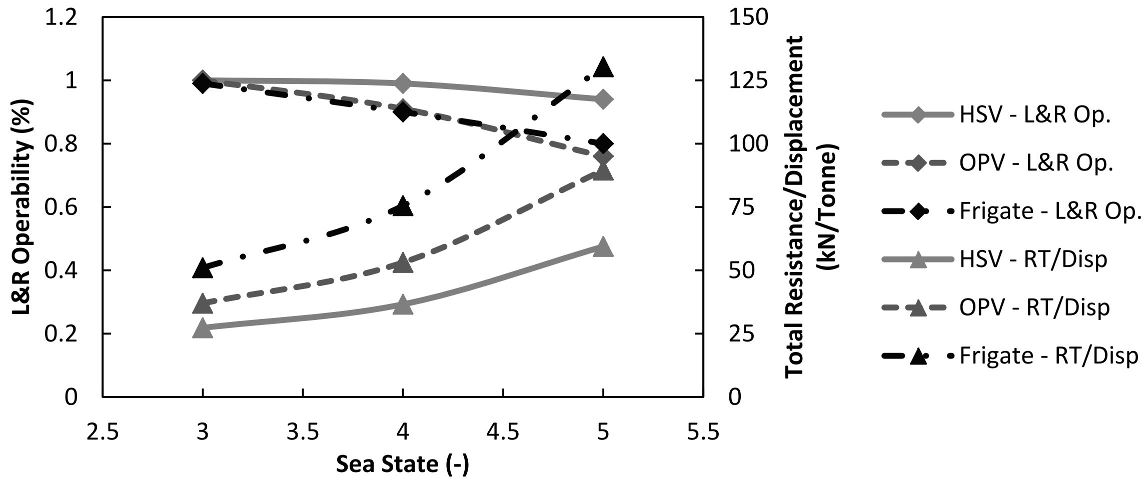

Figure 11. Optimal performances with respect to L&R operability and Total Resistance per tonne Displacement @ 14 knots for each vessel type for increasing sea state

From analysis of both the entire population of design points in Figure 10 and the most optimal regions of the design space in Figure 11, the HSV was able to outperform both the OPV and frigate over all analysed sea states. Though, the differences in performance for each KPP varied between vessel types. Furthermore, these differences were exacerbated in the higher sea states. This indicates that some vessel type hullforms are better suited to exhibit enhanced performance for a particular performance attribute in a specific environment, which is expected. Additionally, the degradation in performance with increasing sea state appeared to be dependent on the vessel type hullform. Hence, some vessel types were impacted to a greater degree by changing wave conditions.

The next section of the results describes the analysis process by which the design space is explored further to gain insight into the existing design relationships that can be exploited to inform defensible design decisions. Where, by what has been articulated in this section of the results discussion, these relationships help to identify feasible OTS solutions that can best satisfy the capability needs.

3.3.2 Hull Design Variable Analysis

The investigation in the previous section demonstrated how the proposed M&S framework could be used to determine the most suitable vessel hullform type to meet a capability need. This section provides an overview of how the M&S framework can be used to further analyse the design space by gaining an understanding of the relationships between hull design variables and the KPPs. Analyses conducted in this section were based on the most suitable hullform type identified in the previous sections, the HSV type. Three key types of hull design variable analyses can be used to inform the Risk Mitigation and Requirement Setting phase activities:

1. Sensitivity Analysis
2. Analysis of Optimal Design Points (as introduced in Section 3.3.1)
3. Response Surface Models

Finally, an example of how the Off-the-Shelf (OTS) ship design marketplace can be ranked by exploiting the knowledge to be gained from these three analyses is described. This example demonstrates how a database of existing vessel designs can be ranked according to their likely performance based on the preferred combination of design parameters. This activity supports definition of requirements that reflect the OTS naval vessel design marketplace by understanding the constraints placed on acquisition stakeholders from the existing solution space [41]. Additionally, this activity can help identify any capability risks associated with the OTS constraint, as the likely mission performance can be estimated and compared to the capability needs.

3.3.2.1 Sensitivity Analysis

For the hydrographic survey capability case study, sensitivity analyses were first conducted by determining the influence on the KPPs by the hull design variables. The term ‘sensitivity analysis’ in the context of this analysis can be defined by Saltelli, Tarantola [42] “as a measure of the effect of a given input on a given output”. Performing a sensitivity analysis is a useful step in the design exploration process since it supports defensible design decisions. A key output of the sensitivity analysis is the determination of design variables that are statistically significant[6], knowledge of which can be used when defining requirements. Subsequently, an inherent outcome of the sensitivity analysis is the determination of design variables that are not statistically significant and therefore can be neglected throughout the remaining analyses.

The metrics for the sensitivity analysis were calculated using the Spearman Rank Correlation Coefficient method [44]. This method was chosen due to its capacity to correlate the strength of a relationship between an input and an output without concern of the relationship being linear, quadratic, or parametric. At this stage of the analysis it is beneficial to determine the strength of a relationship between a design variable and performance. This provides an understanding of which design variables to conduct further analysis on, and which to disregard. The resultant sensitivity metric can be either positive or negative, where the sign of the metric represents the slope of the gradient for the corresponding relationship.

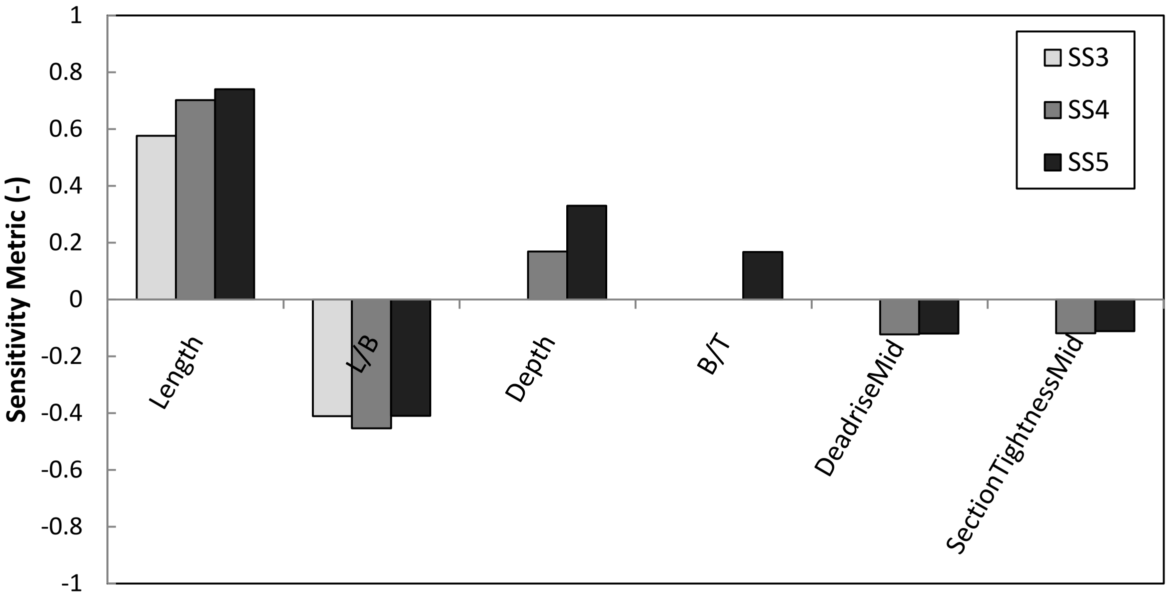

Figure 12. Sensitivity analysis results for the HSV's L&R operability for each sea state

The sensitivity analysis was performed on the design space of the HSV, for each of the three KPPs, and for each of the three sea states. The results for the sensitivity analysis for L&R operability can be seen in Figure 12. Over all sea states there were a total of 6 design variables that were statistically significant for their influence on L&R operability. However, between each sea state the influence of design variables on the L&R operability varied between both number, as well as the magnitude of each corresponding design variables' sensitivity metric. All of the global hull design variables were found to influence the vessels L&R operability between each of the sea states. Conversely, in higher sea states two local hull design variables, deadrise at midships and section tightness at midships,

[6] Variables are considered statistically significant if the corresponding P-value (a factor of the coefficient and number of data samples) falls below 0.05 or 5% Zar, J. H. (1972) Significance testing of the Spearman rank correlation coefficient. *Journal of the American Statistical Association* **67** (339) 578-580.

were found to influence the L&R operability. This suggests that different design variables must be considered when optimising a hullform for operations in particular sea states. Section 3.2.5 gave an overview of the global and local hull design variables, though the main difference is that global variables influence the overall size whilst local variables influence the form and geometry at a specific area on the hullform.

With respect to the strengths of relationships in Figure 12, for a majority of design variables the sensitivity metric increases in magnitude with increasing sea state. This is most recognisable for length, the sensitivity metric for length increases from 0.58 to 0.74 from SS3 to SS5 respectively. This result is expected. For example, a ship of longer length will generally have a greater displacement and therefore experience lesser motions. As the motions of the vessel increase in higher sea states the benefits of increasing length, and thereby displacement, become more significant. Length and L/B, over all sea states, generally have greater sensitivity metrics than other variables and so have greater impact on the performance of the hullform. This suggests that when optimising the HSV hullform the global hull design variables of length and L/B should be of greatest importance.

Figure 13 shows the results of the sensitivity analysis for transit operability. Compared to the results for L&R operability there were a greater number of design variables identified as having a significant influence on transit operability. This suggests that a greater number of hull design variables may be considered for the optimisation of a hullform for transit based seakeeping activities.

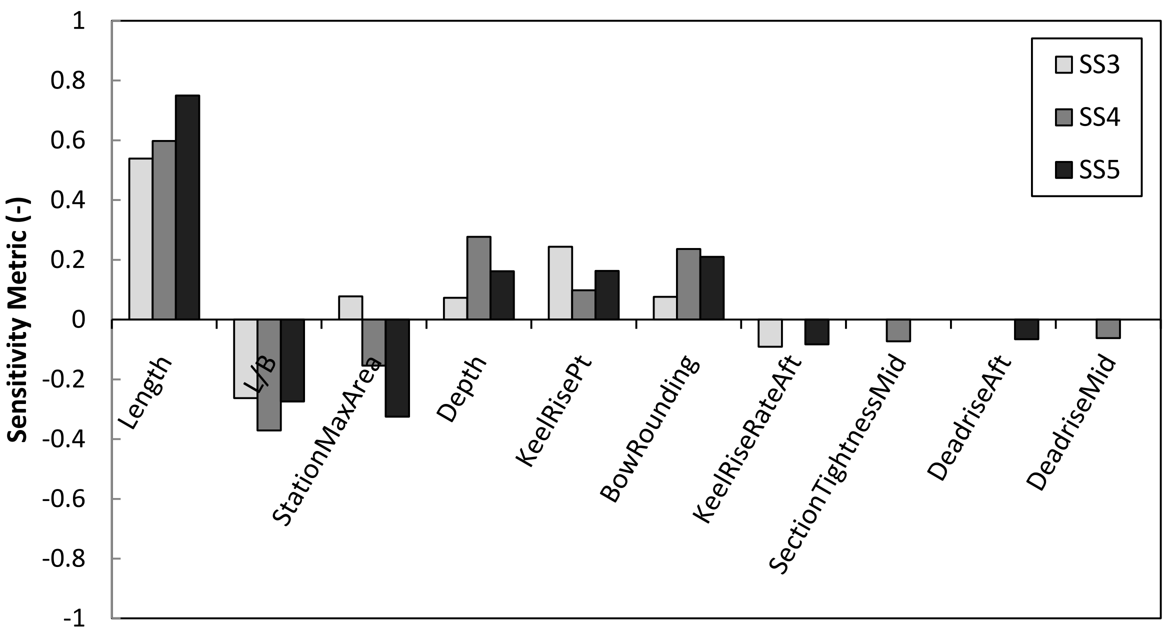

Figure 13. Sensitivity analysis results for the HSV's transit operability for each sea state

Of interest, there were a large number of local hull design variables that were found to influence the transit operability. Furthermore, a number of local hull design variables, namely the location of the maximum station area, keel rise point and bow rounding had greater sensitivity metrics than some of the global hull design variables in particular sea states. These results demonstrate that for certain KPPs and in particular operating environments the performance of the HSV can be improved by addressing specific local features of the hullform. For example, Figure 13 indicates that varying the local hull design variable, location of the maximum station area in SS5 has a greater impact on transit operability than altering the global hull design variable, L/B.

The results of the sensitivity analysis for R_T/Δ at 14 knots can be seen in Figure 14. Over all sea states there were a total of six design variables identified as statistically significant for their influence on the total resistance per tonne displacement (R_T/Δ) at 14 knots. In a similar manner to the two seakeeping operability KPPs, both the total number and magnitude of the corresponding sensitivity metric varied between each sea state.

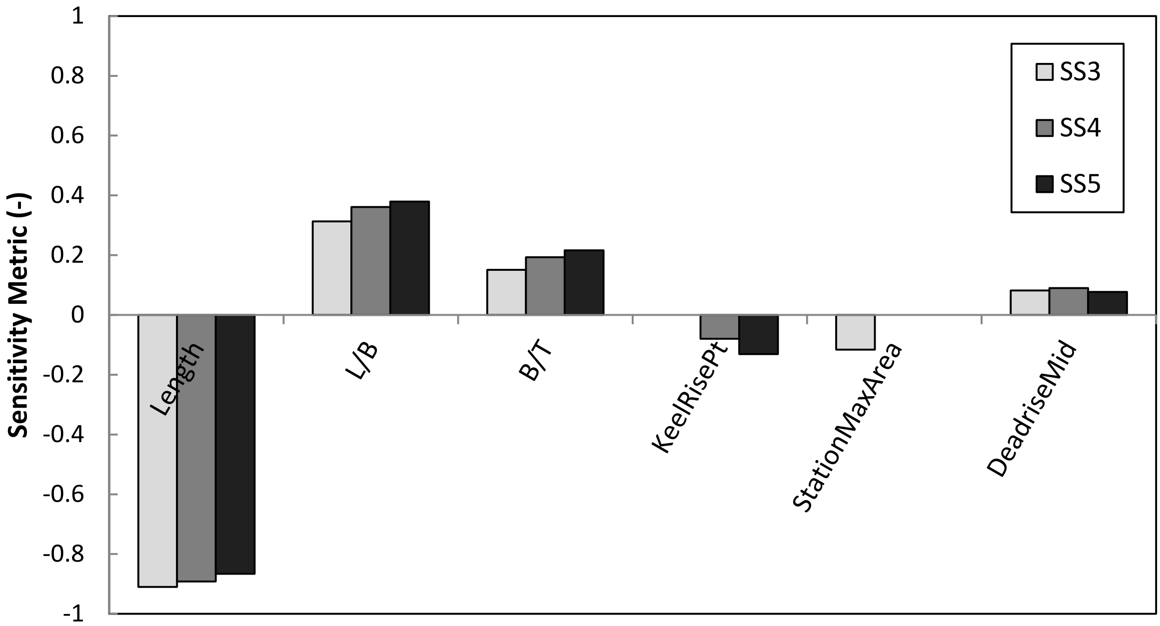

Figure 14. Sensitivity analysis results for the HSV's Total Resistance per tonne Displacement for each sea state

It can be seen from Figure 14 that four of the six design variables were common for all sea states; length, L/B, B/T and deadrise at midships. Of the four hull design variables, deadrise at midships is the only local hull design variable. This suggests that irrespective of the sea state, global hull design variables have a greater influence on R_T/Δ than local hull design variables. For SS3 only, the location of the maximum station area was also identified as a design variable. While, for SS4 and SS5, the location of the keel rise point was identified as an additional statistically significant design variable.

Assessing the strength of each relationship, from Figure 14 there is correlation between the magnitude of the sensitivity metric and the sea state for all the global hull design variables; length, L/B and B/T. For length, the sensitivity metric decreased in magnitude from SS3 to SS5 respectively. Conversely, L/B and B/T both increased in magnitude from SS3 to SS5. It appears no such relationships between sensitivity metric magnitude and sea state exist for the local hull design variables i.e. keel rise point, station max area and deadrise at midships. Considering all sea states, the global design variables had the greater sensitivity metrics further supporting that R_T/Δ can be optimised most significantly by addressing primarily the global hull design variables of length, L/B and B/T.

Table 7. Sensitivity analysis results summary. Sensitivity metrics represent the average sensitivity metric over all sea states

Design Variables	Variable Type	L&R Operability	Transit Operability	R_T/Δ @ 14 knots
Length	Global	0.673	0.629	0.889
L/B	Global	-0.425	-0.303	0.351
B/T	Global	0.167		0.187
Deadrise Midships	Local	-0.122	-0.062	0.083
Depth	Global	0.250	0.171	
Station Max Area	Local		-0.134	-0.116
Keel Rise Point	Local		0.168	-0.106
Section Tightness Midships	Local	-0.116	-0.073	
Bow Rounding	Local		0.174	
Keel Rise Rate Aft	Local		-0.087	
Deadrise Aft	Local		-0.066	

Table 7 summarises the sensitivity analysis results by listing all design variables that were identified as statistically significant for each KPP, the sensitivity metrics presented were the corresponding averages over all sea states. In total there were 11 hull design variables determined as statistically significant. A majority of these design variables were common across at least 2 of the KPPs. Length and L/B were consistently the most prevalent hull design variables across all KPPs. Therefore, the hydrographic survey vessel's performance considering all KPPs can be optimised to the greatest extent by variation of two key global hull design variables: length and L/B. However, further optimisation can be attained incrementally by variation of the remaining global and local hull design variables highlighted throughout this section of the discussion to achieve an overall optimised capability from the HSVs' design space. As discussed in this section, improving the performance of the HSV through the remaining hull design variables (disregarding length and L/B) will depend on the particular conditions the hullform needs to be optimised for, i.e. what KPPs will have preference for stakeholders? And what environmental conditions are of most importance? This knowledge could be used during the Risk Mitigation and Requirement Setting phase to constrain the range of design variables in the request for tender requirements, which would ensure only suitable designs are received in response.

3.3.2.2 Optimal Design Points Analysis

Analysis of the most optimal region of the HSV's design space concerns investigating the value of hull design variables comprising those design points optimised for maximum L&R operability and minimum R_T/Δ at 14 knots. For this reason, statistically significant hull design variables in relation to transit operability were neglected throughout this section of the discussion. Design points comprising the most optimal regions of the design space (the pareto-fronts) of the HSV for all sea states can be seen in Table 8. Corresponding design variables for each design point is listed, statistically significant hull design variables are shaded grey for convenience. The pareto-fronts of the HSV in SS3, SS4 and SS5 comprised of one, two and six design points respectively.

Table 8. Summary of design points and their respective hull design variables that populated the pareto-fronts of the HSV for each of the analysed sea states

	SS3	**SS4**		**SS5**					
Design Variables	Design Point 775	Design Point 775	Design Point 337	Design Point 775	Design Point 337	Design Point 347	Design Point 229	Design Point 418	Design Point 135
Length (m)	95	95.0	94.2	95.0	94.2	94.2	91.0	91.8	93.4
L/B	4.12	4.12	4.26	4.12	4.26	4.58	4.23	4.05	4.12
B/T	3.34	3.34	3.47	3.34	3.47	3.29	3.50	3.93	3.95
Depth (m)	10.31	10.31	10.00	10.31	10.00	10.55	10.37	10.43	10.55
Station Max Area	0.466	0.466	0.544	0.466	0.544	0.427	0.418	0.417	0.515
Prismatic Control	0.338	0.338	0.502	0.338	0.502	0.483	0.502	0.376	0.367
Section Tightness Aft	0.537	0.537	0.692	0.537	0.692	0.450	0.624	0.731	0.489
Section Tightness Fwd	0.805	0.805	0.766	0.805	0.766	0.902	0.891	0.931	0.766
Section Tightness Mid	0.485	0.485	0.418	0.485	0.418	0.350	0.398	0.389	0.553
Deadrise Aft	0.656	0.656	0.550	0.656	0.550	0.695	0.753	0.637	0.831
Deadrise Fwd	0.531	0.531	0.453	0.531	0.453	0.356	0.289	0.250	0.327

Deadrise Mid	0.168	0.168	0.065	0.168	0.065	0.103	0.058	0.065	0.129
Slope Aft	0.056	0.056	0.250	0.056	0.250	0.218	0.016	0.242	0.145
Slope Fwd	0.708	0.708	0.844	0.708	0.844	0.873	0.698	0.718	0.882
Flare Fwd	0.68	0.680	0.911	0.680	0.911	0.931	0.931	0.873	0.94
Stem Rake	28.45	28.45	23.57	28.45	23.57	23.28	20.41	25.58	22.71
Stem Curvature	0.373	0.373	0.334	0.373	0.334	0.431	0.189	0.363	0.218
Bow Rounding	0.0484	0.0484	0.184	0.0484	0.184	0.087	0.300	0.087	0.29
Forefoot Shape	0.402	0.402	0.189	0.402	0.189	0.431	0.45	0.363	0.237
Transom Rake	-14.07	-14.07	-14.44	-14.07	-14.44	-13.19	-14.20	-11.55	-12.94
Transom Deck Width	0.831	0.831	0.984	0.831	0.984	0.879	0.823	0.782	0.766
Keel Rise Point	0.753	0.753	0.715	0.753	0.715	0.811	0.763	0.821	0.84
Keel Rise Rate Aft	0.189	0.189	0.460	0.189	0.460	0.450	0.286	0.179	0.237
Keel Rise Rate Fwd	0.146	0.146	0.292	0.146	0.292	0.185	0.166	0.05	0.195

From Table 8 design point 775 was located on the pareto-fronts of the HSV in all sea states. Additionally, design point 337 was located on the pareto-front of the HSV in both sea states 4 and 5. In all occurrences design point 775 was the non-dominated design point with a minimum R_T/Δ measure. Moreover, in SS3 design point 775 also had the maximum L&R operability. From the ranges of global hull design variables investigated from Table 1, design point 775 had the longest possible length, a low L/B, a low B/T and a large depth. In SS4 design point 337 was the non-dominated design with a maximum L&R operability. Design point 337 had a length close to the upper limits of the ranges for the hull design variables shown in Table 1, a low L/B, a low B/T and a large depth. In SS5 design point 135 was the non-dominated design with a maximum L&R operability. Similar to design point 337, design point 135 had a length near the upper limits of the ranges for the design variables shown in Table 1, a low L/B, and the largest possible depth. A key difference between design point 135 from design points 775 and 337 was a high B/T, this can be attributed to the fact that for L&R operability B/T was a statistically significant design variable for SS5 only, as shown in Figure 12. There were many similarities between global hull design variables when comparing design points 775, 337 and 135. Similarities between the global hull design variables reflect the findings from the sensitivity analysis from

Section 3.3.2.1. Length overall and L/B both consistently had the highest sensitivity metrics (greatest influence on KPPs), while B/T and depth also had relatively high sensitivity metrics. Due to the greater influence on the KPPs from the sensitivity analysis and the similarities between values for design points on the pareto-fronts, global hull design variables have the greatest contribution towards the hullform design achieving optimal performance.

Also a reflection of the high sensitivity metrics of the global hull design variables, all design points from the pareto-fronts had very similar global geometric characteristics. All designs had a length overall of greater than 90 m, a low L/B less than 4.6, and a depth greater than 10 m. The results for B/T were the most widespread for global hull design variables with design points 418 and 135 having a high B/T, while the remainder of design points were low. As previously mentioned, this can be attributed to the increase in the B/T sensitivity metric strength for L&R operability in SS5.

Analysis of the most optimal region of the design space for the HSV has determined that statistically significant hull design variables contribute most to achieving optimal performance. Global hull design variables of each design point on the pareto-fronts consistently achieved similar values. This result supports the outcomes from the sensitivity analysis covered in Section 3.3.2.1. Global hull design variables, especially length and L/B, had the greatest sensitivity metrics (see Table 7), and therefore the strongest relationship to performance. This is reflected by the similar values of length and L/B of each design point exhibiting optimal performance. Furthermore, assessing the range of hull design variable values provides insight into the required values that result in improved performance. Local hull design variables compared to global hull design variables did not consistently achieve similar values. The weaker correlation between the values of local hull design variables was associated with the relatively low sensitivity metrics achieved in the sensitivity analysis, Section 3.3.2.1. While similarities between local hull design variables were recognised, the strength of their relationships on performance was less than that determined for global hull design variables. Provided with this information, during requirements setting activities, the designer has an understanding of:

- *Which hull design variables have the strongest relationships between certain KPPs* – complimenting the results of the sensitivity analysis, which provides acquisition stakeholders with a better understanding of which design variables to include or disregard within tendering documentation in order to improve performance.

- *Which values of hull design variables contribute to improved KPPs* – provides acquisition stakeholders with an understanding of the range of values that materialise into a capability with optimal performance.

3.3.2.3 Response Surface Models

At this stage of the acquisition process the requirements have been elucidated since the acquisition stakeholders have gained a better understanding of the impact of requirements on the design of the ship. All that remains is for the stakeholders to finalise design decisions by setting the requirements, thereby developing the technical specifications that will be released to industry. Through the creation of the simulation workflow, generation and exploration of the design space, it has been shown how the M&S framework is able to aid defensible design decisions. Sequentially, throughout the process, the design decisions have evolved from broad to more detailed. Response Surface Models (RSMs) can provide stakeholders with the final remaining level of information enabling the more detailed design decisions to be resolved; in particular, setting the requirements in light of the OTS constraint on the vessels that can be acquired to meet the capability needs. RSMs can be used to support identification of any capability risks imposed by the OTS constraint, as they allow the mission performance of OTS designs to be estimated.

Response Surface Models are derived from Response Surface Methodology originally proposed by Box and Draper [45]. Response Surface Methodology is a collection of mathematical and statistical techniques used in combination with DOE to generate a response (output variable) which is influenced by several independent variables (input variables). In the context of the hydrographic survey capability case study, an RSM is a design exploration tool that formulates the relationships between hull design variables and KPPs. Simultaneously using RSMs for each of the KPPs provides acquirers with a predictive measure of the vessels overall performance for any combination of input hull design variables. Utilising RSMs in this manner and given the level of design information known to the designer at this stage of the design exploration process, the designer can efficiently determine the values of hull design variables that maximise the KPPs and optimise the overall capability. This information can be used to interrogate a database of existing vessel designs and identify any capability risks associated with the OTS constraint as described in [41]. The requirements can then be set to replicate those hull design variables, in the form of a technical specification, constraining the possible design space to only those technical solutions that will adequately meet the capability need.

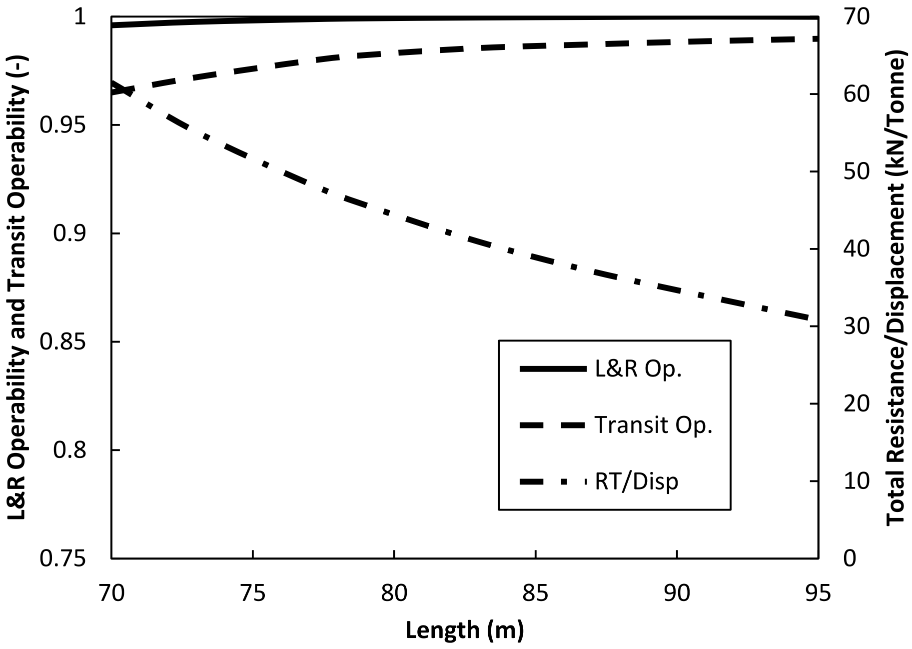

Figure 15. Response Surface Models of the HSV's length with respect to each of the three KPPs in sea state 3

Figure 15 shows RSM's of the HSV type hullform for each of the three KPPs covered in this case study in SS3 with respect to the length of the vessel. When interpreting the plot both L&R and transit operability are referenced to the left y-axis and R_T/Δ at 14 knots is referenced to the right y-axis. From Figure 15 as the length of the vessel increased both L&R and transit operability indices increased marginally as well as the R_T/Δ decreased. Therefore, to achieve an optimal capability in SS3 the length of the vessel should be close to 95 m, the longest length investigated in this report. This supports the results from Section 3.3.2.2, the most optimal design point in SS3 had the longest possible length.

While a HSV length of 95m would achieve optimal performance, the gradients of the trends for L&R and transit operability in Figure 15 indicate that in SS3 any length of vessel above approximately 80 metres would result in greater seakeeping performance. Both operability indices increased by <1% from 80 m to 95 m. Conversely, improvements in resistance performance can be gained by increasing the length of the vessel from the minimum length of 70 m to the maximum length of 95 m. Over this range of vessel length, the R_T/Δ measure decreased from approximately 60 kN/Tonne to 30 kN/Tonne; a 50% improvement.

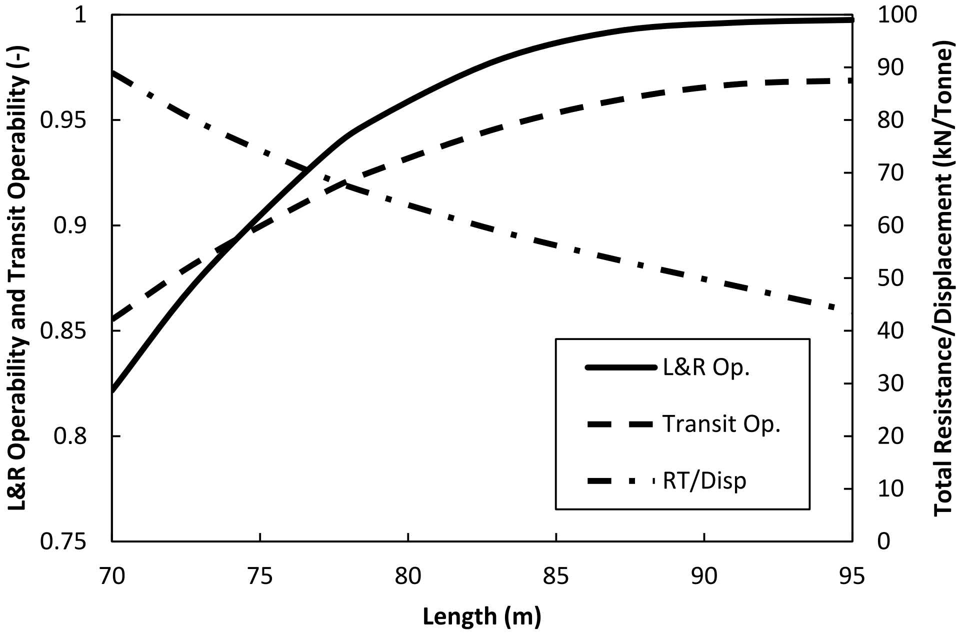

Figure 16. Response Surface Models of the HSV's length with respect to each of the three KPPs in sea state 4

Figure 16 shows RSM's of the HSV type hullform for each of the three KPPs in SS4 with respect to the length of the vessel. Similar to the trends from SS3, as the length of the vessel increased both L&R and transit operability increased as well as the R_T/Δ decreased. Comparing the gradients of the trends for L&R and transit operability from figure 16 to Figure 15, it can be seen that the influence of length on the KPPs in SS4 is more significant than in SS3. This result was expected since the sensitivity metrics for length for both L&R and transit operability in Figure 12 and Figure 13 respectively, increased with increasing sea state.

Similar to Figure 15, the gradients of the trends indicate that for L&R and transit operability any HSV length above approximately 90 metres would result in greater seakeeping performance. Increasing the length of the vessel from 90 m to 95 m would increase the L&R and transit operability indices by <1%. In comparison to SS3, these results suggest that a longer vessel length is needed in higher sea states to achieve the desired levels of seakeeping performance. Furthermore, similar to Figure 15 the R_T/Δ from approximately 90 kN/Tonne to 45 kN/Tonne by increasing the vessel length from 70 m to 95 m respectively; a 50% improvement. Therefore, setting a length constraint in the requirements of vessels around 90-95 m would result in optimal performance for all three KPPs in SS4.

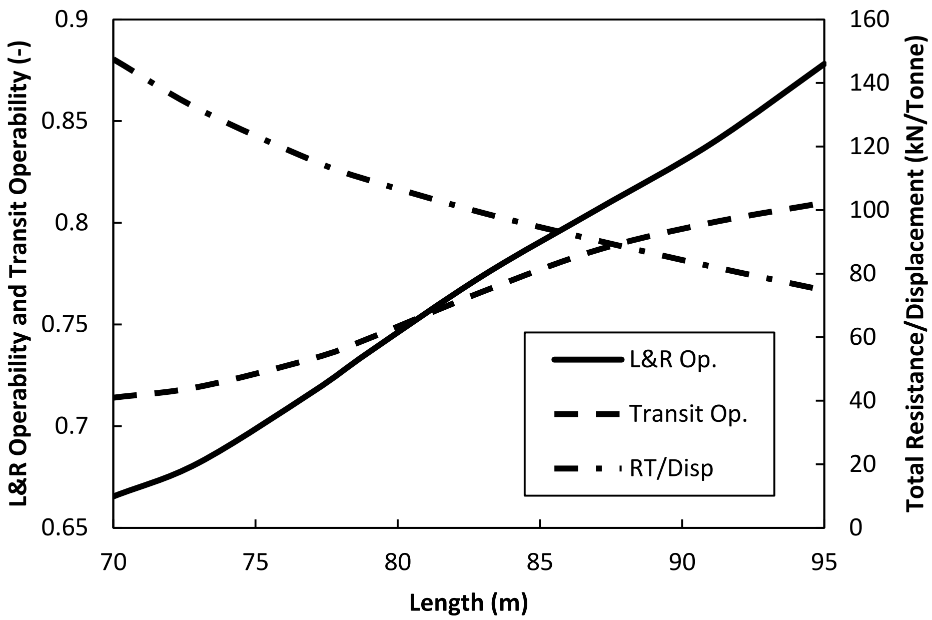

Figure 17. Response Surface Models of the HSV's length with respect to each of the three KPPs in sea state 5

Figure 17 shows RSM's of the HSV type hullform for each of the three KPPs in SS5 with respect to the length of the vessel. The same trends in SS5 occurred in both SS3 and SS4. With increasing vessel length both L&R operability and transit operability increased as well as the R_T/Δ decreased. The gradient of the trend lines, or relationships between length and both L&R and transit operability differed in SS5 to the observed gradients in SS3 and SS4 from Figure 15 and Figure 16 respectively. The influence of length on L&R and transit operability is most significant in SS5. As stated in the previous paragraph, this was an expected result since the sensitivity metrics for length for both L&R and transit operability were greatest in SS5. From Figure 17, increasing the length of the vessel from 70 m to 95 m would increase the L&R operability by approximately 21% and the transit operability by 10%. Likewise, the R_T/Δ would decrease from approximately 150 kN/Tonne to 75 kN/Tonne; a 50% improvement in R_T/Δ as occurred in both SS3 and SS4. Therefore, to achieve an optimal capability by maximising each of the three KPPs the length of the HSV should be as long as possible. For the proposed case study, the requirement for the vessels length should be set to constrain vessel length to be as close to 95 m as possible. It is worth noting this recommendation only considers the KPPs used in this case study. In reality, there will be competing objectives, such as acquisition and through-life operating costs, which will generally be higher for larger vessels. This means that the analysis described above facilitates the conducting of trade-offs between competing objectives, which inevitably occurs in defence acquisitions. Following is a discussion of how RSMs can facilitate trade-off decisions for competing objectives, which uses competing hull design variables.

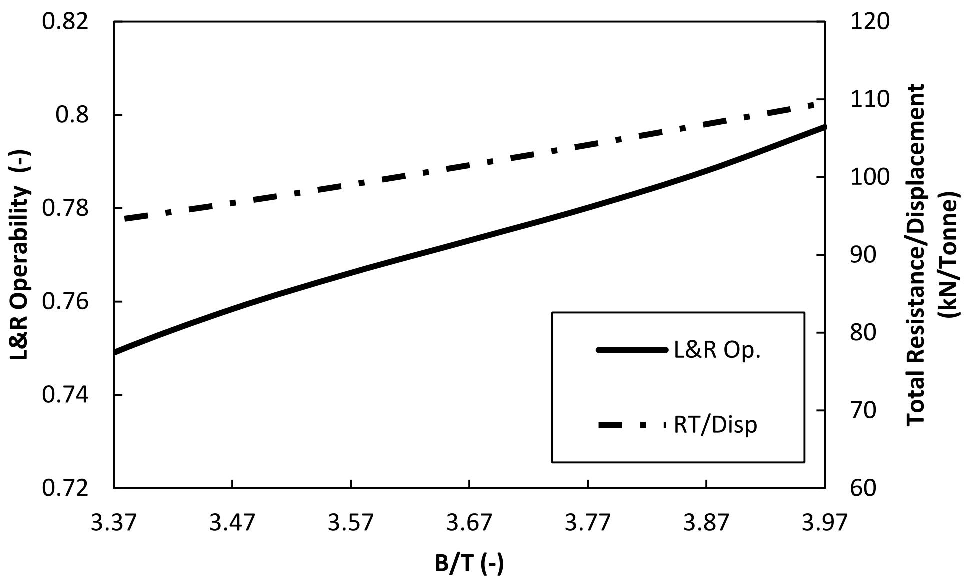

Figure 18. Response Surface Models of the HSV's B/T with respect to the L&R operability and Total Resistance per tonne Displacement in sea state 5

Figure 18 shows the RSM's for the L&R operability and R_T/Δ in SS5 against the vessel's beam to draft ratio (B/T). Note that transit operability was omitted in this figure for clarity between direct comparisons of competing requirements. It can be seen that an increase in B/T resulted in an increase for both the L&R operability and R_T/Δ. Figure 18 provides a suitable example for using RSMs to assist design trade-off decisions. Setting the requirement for B/T to the minimum of the range would result in optimal R_T/Δ performance. However, this would compromise the vessels L&R operability performance as a minimum B/T also resulted in the worst L&R operability. Contrarily, setting the B/T to the maximum of the range would result in optimal L&R operability and the worst R_T/Δ performance. Hence, there is a trade-off for setting the requirement for the vessels beam and draft, or essentially the B/T.

Resolving the trade-off design decision may be as simple as setting the B/T to maximise the KPP that is most significant to the overall capability need. For example, capability acquisition stakeholders may regard the L&R seakeeping performance of the HSV to be more important than the resistance performance. This suggests seeking OTS designs with high B/T to maximise the L&R seakeeping performance.

Using the example for setting the requirement for length, it has been shown how RSMs can be used to determine what value of length to set in order to maximise each of the three KPPs. This process would need to be repeated for each of the statistically significant hull design variables in order to develop the full technical specification that characterises a hullform that leads to an optimal capability. Where there are competing requirements or trade-offs between hull design variables as well as other KPPs such as costs, it was detailed how RSMs could be used to understand the consequences of the trade-off in order to consolidate the required values of hull design variables contributing to an improved capability.

3.3.2.4 Ranking Off-the-Shelf Ship Designs Using Knowledge Gained

This activity uses the knowledge gained from the previous analyses to build, then rank a database of existing vessel designs based on the preferred combinations of design variables. For the indicative hydrographic survey capability, a database of existing designs was built from relevant existing vessel design data contained in the Janes IHS database [46, 47]. Then, using the knowledge gained about the hullform design variable sensitivities from Section 3.3.2.1, the vessels in the database were ranked. Two key design variables were used to rank the designs. The first ranking criterion was vessel length, since increasing vessel length had the highest sensitivity metric and therefore the greatest influence on all KPPs. The second ranking criterion was the length-to-beam (L/B) ratio, since the L/B ratio had the second greatest sensitivity metric. Other hull design variables could have been used to rank the designs, however, a shortcoming of the database used for this example were the limited number of vessel parameters it contained. This will be a shortcoming present in most OTS acquisitions as the acquirer is unlikely to have access to extensive OTS vessel design data.

In the hydrographic survey capability example, the vessel ranking was performed using the multi-attribute value analysis method, where the overall weighted value of each vessel in the database was calculated based on a summation of the swing weights of its length and L/B ratio. The weights were calculated from the ranks of the sensitivities of the hull design variables (vessel length first and L/B second) using the Rank Order Centroid technique from Buede [48]. Value curves for length (greater value as it increases) and the length-to-beam ratio (greater value as it decreases) were assumed to be linear with a positive and negative gradient respectively. Design data for the top ten vessels in the database with lengths between 65 and 95 metres is shown in Table 9.

Table 9. Top ten ranked designs from the vessel database based on vessel length and L/B; data obtained from [47]

Rank	Displacement (tonnes)	Length (m)	Beam (m)	Length /Beam	Speed (knots)	Range (nm)	Crew
1	6421	89.9	19.1	4.71	15	12 000	33
2	2889	87	14.6	5.96	15	12 000	31
3	3477	85.7	15	5.71	14	11 000	58
4	3455	83.5	16	5.21	15	11 300	22
5	2991	85	14.1	6.03	14	10 060	23
6	3024	72.5	15.24	4.76	12	10 500	20
7	2164	76.8	12.8	6.00	14.5	10 000	24
8	2205	71.2	15.2	4.68	14	18 000	61
9	2382	67.5	15.3	4.41	16.5	22 000	22
10	2298	68.3	13.1	5.21	11	19 000	49

The top-ranked designs from the database can be investigated further to establish their suitability against the capability needs. In this stage of the investigation, aspects such as the operating navy, year of design and country of origin of the designer can be established, as well as refinement of the top-ranking vessels based on other requirements, such as the range and crew size.

In considering whether there are any capability risks for the operational needs described in Section 3.2.1 due to the OTS constraint, the data from the top-ranking existing vessels can be cross-checked against the data from the design space generated in the previous analyses. By comparing the top-ranked existing designs in Table 9 with the top performing generated designs in Table 8, some inferences can be drawn. Firstly, there does not appear to be many existing designs with vessel particulars similar to the optimal designs in Table 8. This could suggest some of the top performing generated designs may be unrealistic and therefore not feasible, or conversely, there is a gap in the marketplace. RSMs can be used to investigate this further. From Figure 15 and Figure 16, it can be seen that the slope of both the launch and recovery (L&R) and transit operability indices decrease as the vessel length grows from approximately 85 metres to 95 metres. This means there is likely to be only marginal improvements in the seakeeping performance of designs longer than 90 metres and up to the 95 metre limit, especially when operating in SS4. In regards to improved performance in SS3 and SS4, acquisition stakeholders can have confidence that the existing vessels larger than roughly 85 metres in length, provided they have a typical hydrographic survey vessel hullform, will have high L&R operability and be capable of meeting the operational needs. This implies there is only low capability risk and there will be no need to revisit the requirements in order to replicate the likely performance of naval vessels in the existing marketplace.

This information can support acquisition stakeholders make design decisions in regards to design changes. Although this technically violates the OTS constraint, some design changes from the existing design are typically made due to legislative and other requirements differences. If the design changes are affordable, it seems to make sense to pursue changes that could increase performance for the KPPs of the naval vessel being acquired. Requirements released to industry could be driven by these design changes if the capability risk is too high. Otherwise, requirements should reflect the combination of parameters that contribute to improved performance in light of a low capability risk, as outlined in the previous paragraph.

4. Conclusion

The development of a Ship Performance M&S framework that can be used to assist capability acquisition stakeholders with the development of requirements in the *Risk Mitigation and Requirement Setting* phase of the Capability Life Cycle (CLC) has been presented. The Modelling and Simulation (M&S) framework was aligned with a Model-Based Systems Engineering Methodology (MBSE) [18] to facilitate traceability between the requirements, design variables and ship performance. The case study covered included the acquisition of a new hydrographic survey capability. The aim of the study was to act as a proof of concept for analysing the impact of vessel type and hullform design for the suitability to meet an indicative hydrographic survey capability need. The capability needs, described in Section 3.2.1, were used to generate a design space for exploration through implementation of the M&S framework. Three representative vessel hullforms were considered for meeting the capability needs: a Hydrographic Survey Vessel (HSV), an Offshore Patrol Vessel (OPV) and a frigate. Analysis of the results was separated into two sections to detail how the design space can be explored effectively to assist the development of requirements and an understanding of the Off-the-Shelf (OTS) constraint on ADOD acquisitions.

In the vessel hullform type comparison, the design space was explored through application of 2D scatter plots and histogram plots. Utilising these trade study tools was shown to be effective for understanding performance results of the design spaces for each of the three vessel hullforms. Analysis of the 2D scatter plots determined that the most optimal region of the design space (the pareto-front) for the HSV hullform achieved the overall best performance for L&R operability, transit operability and R_T/Δ over sea states 3, 4 and 5. Analysis of the histogram results verified that the HSV hullform was the most suitable vessel type over all sea states. Histogram results were able to demonstrate the change in performance between each hullform type for increasing sea states. L&R and transit operability performance diminished at a faster rate for the HSV than the OPV and frigate with increasing sea states from 3 to 5. While the HSV still achieved best performance for all KPPs in sea state 5, these results were able to show how different vessel types are better suited to exhibit enhanced performance in particular ocean environments. Application of the M&S framework to explore the design space for possible vessel hullform types was shown to be successful as a means of informing capability acquisition stakeholders of the most suitable vessel type to meet an optimal capability need.

After supporting the selection of the most appropriate vessel hullform, the design space was explored further by analysing the hull design variables that contribute to an optimal capability through application of a sensitivity analysis and Response Surface Models (RSMs). Incorporating the sensitivity analysis at the initial stage of the hull design was shown to be a successful means of determining which hull design variables were statistically significant for their influence on the mission performance KPPs. Global hull design variables, especially length and L/B, were determined to have the greatest influence on each of the KPPs. A number of local hull design variables were also found to have an influence on each of the KPPs; this included the deadrise at the ships midships and the location at which the keel starts to rise. Application of the sensitivity analysis was shown to be an efficient approach to determine which of the design variables capability acquisition stakeholders should give preference during requirement setting activities.

Detailed assessment of the design points that formed the pareto-fronts of the HSV for sea states 3, 4 and 5 was shown to be beneficial for providing an understanding of the combinations of hull design variables that contribute to optimal mission performance. Furthermore, analysis of design points comprising the pareto-fronts was able to compliment the results of the sensitivity analysis providing a deeper understanding of the hull design variables that have the strongest relationship between certain KPPs, and which contribute to an overall optimal capability.

Application of RSMs was shown to be a successful tool for assisting capability acquisition stakeholders finalise design decisions and set requirements. It was shown how RSMs could be used to understand the relationship between hull design variables and KPPs. A detailed understanding of these relationships, along with knowledge gained from the sensitivity analysis and examining the optimal region of the design space could be used to conduct an initial screening of existing OTS naval vessels. After ranking top designs based on their likely mission performance, RSMs could be exploited to assist with the identification of any capability risks due to the constraints from the OTS marketplace. With regards to mission performance in sea states 3 and 4, it was determined that there was a low capability risk associated with the top ranked OTS naval vessels. This activity was able to highlight the improvement in performance of an optimised hullform as opposed to those in the OTS marketplace. This understanding, depending on the significance of the capability risk, could drive designers to make design changes in the form of requirements released to industry. Overall, it was demonstrated how use of RSMs and other aforementioned analyses can assist acquisition stakeholders with defensible design decisions during the *Risk Mitigation and Requirement Setting* phase.

Implementing the Ship Performance M&S framework and aligning it with the MBSE methodology during the *Risk Mitigation and Requirement Setting* phase of the CLC can provide capability acquisition stakeholders with an improved understanding and more thorough definition of the requirements for a proposed capability need. The outcomes of implementing the M&S framework ensures that the requirements released to industry, the primary output of this phase of the CLC, constrains the technical solutions to only those OTS designs that adequately meet the capability need. Thereby, the M&S framework can contribute to Defences ambition of becoming a smart buyer in an OTS naval vessel acquisition. Subsequent reports will cover how the Ship Performance M&S framework can be used to support the Acquisition phase (Part 2) and In-Service and Disposal phase (Part 3) of the CLC.

5. References

1. Defence (2016) *2016 Defence White Paper*
2. Defence (2015) *First Principles Review | Creating One Defence*.
3. Defence (2017) *Naval Shipbuilding Plan*.
4. Defence (2016) *Navy's Operationalisation of the Naval Shipbuilding Plan*.
5. Defence (2016) *Interim Capability Life Cycle Manual*.
6. McDonald, T. P., Andrews, D. J. and Pawling, R. G. (2012) A demonstration of an advanced library based approach to the initial design exploration of different hullform configurations. *Computer-Aided Design* **44** (3) 209-223
7. Dwyer, D. M. and Morris, B. A. (2018) *Part 2 - Acquisition [In Draft]*. Canberra, Australia,
8. Dwyer, D. M. and Morris, B. A. (2018) *Part 3 - In-Service and Disposal [In Draft]*. Canberra, Australia,
9. Andrews, D. (1998) A comprehensive methodology for the design of ships (and other complex systems). In: *Proceedings of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*. Vol. 454, The Royal Society
10. Clark, D., Jones, R. and Sheridan, D. (1984) The ASSET Program- A Current Navy Initiative. In: *Society of Naval Architects and Marine Engineers STAR Symposium*
11. Andrews, D. (2003) A Creative Approach to Ship Architecture.(Awarded RINA Medal 2004). *Transactions of RINA, Part A: International Journal of Maritime Engineering* **145** (3) 229-252
12. Brown, A. and Thomas, L. M. (1998) Reengineering the Naval Ship Concept Design Process, From Research to Reality. In: *Ship Systems Engineering Symposium, ASNE*, Citeseer
13. Faulconbridge, I. and Ryan, M. J. (2014) *Systems Engineering Practice*. Canberra, Australia, Argos Press
14. Kerns, C., Brown, A. and Woodward, D. (2011) Application of a DoDAF total-ship system architecture in building a design reference mission for assessing naval ship operational effectiveness. In: *ASNE Global Deterrence and Defense Symposium*
15. Winyall, D., Edwards, J. and Brown, A. (2012) 3D hullform modeling to support naval ship design synthesis and multi-objective optimization. In: *International Ship Design Conference (ISDC), Glasgow, Scotland*
16. Morris, B. A. (2014) Blending Operations Analysis and System Development During Early Conceptual Design of Naval Ships. In: *SETE 2014,* Adelaide
17. Morris, B. A. and Sterling, G. (2012) Linking the defence white paper system architecture using an aligned process model in capability definition.
18. Morris, B. A. and Thethy, B. S. (2015) Towards a Methodology for Naval Capability Concept and Requirements Exploration in an Off-the-Shelf Procurement Environment. In: *Pacific 2015 International Maritime Conference*: 22/07/2015
19. Morris, B. A., Cook, S. C. and Cannon, S. M. (2018) A Methodology to Support Early Stage Off-the-Shelf Naval Vessel Acquisitions. *The Transactions of the Royal Institution of Naval Architects*

20. Dwyer, D. M. and Morris, B. A. (2017) A Ship Performance Modelling and Simulation Framework to Support Requirements Setting. In: *Pacific 2017 International Maritime Conference,* Sydney, Australia
21. Zeigler, B. P., Praehofer, H. and Kim, T. G. (2000) *Theory of modeling and simulation: integrating discrete event and continuous complex dynamic systems*, Academic press
22. Sinha, R., et al. (2001) Modeling and simulation methods for design of engineering systems. *Journal of computing and information science in engineering* **1** (1) 84-91
23. Sanders, P. (1997) Simulation based acquisition. *Program Manager* **26** (140) 72-76
24. Aughenbaugh, J. M. and Paredis, C. J. (2004) The role and limitations of modeling and simulation in systems design. In: *2004 ASME International Mechanical Engineering Congress and Exposition*
25. Phoenix Integration Inc. *Products*. (2017) [Accessed 2018] Available from: https://www.phoenix-int.com/products/.
26. Robert McNeel & Associates (2017) *Rhinoceros*.
27. DRS Technologies Inc (2016) *Orca3D User Manual*.
28. Holtrop, J. and Mennen, G. (1982) An approximate power prediction method.
29. Faltinsen, O. (1980) Prediction of Resistance and Propulsion of a Ship in a Seaway. In: *Proceedings of 13th Symposium on Naval Hydrodynamics*
30. McTaggart, K. A. (1997) *Added Resistance Prediction in SHIPMO7 Using a Near-Field Method*. Defence Research Establishment Atlantic Dartmouth (Nova Scotia)
31. McTaggart, K. A. (1997) *SHIPMO7: An Updated Strip Theory Program for Predicting Ship Motions and Sea Loads in Waves*. DTIC Document
32. Molland, A. F., Turnock, S. R. and Hudson, D. A. (2011) *Ship resistance and propulsion: practical estimation of propulsive power*, Cambridge University Press
33. DEF (AUST) 5000 (2003) *ADF Maritime Materiel Requirements Set: Volume 3: Part 6: Seakeeping*. Canberra, ACT, Australia, Royal Australian Navy
34. Bentley Systems Inc (2015) *MAXSURF*.
35. DEF (AUST) 5000 (2003) *ADF Maritime Materiel Requirements Set: Volume 3: Part 2: Stability of Surface Ships and Boats*. Canberra, ACT, Australia, Royal Australian Navy
36. Parsons, M. (2003) Chapter 11, Parametric Design. In: *Ship Design and Construction*. Vol. 1 and 2.
37. Crowder, J. A., Carbone, J. N. and Demijohn, R. (2016) The Overall Systems Engineering Design. In: *Multidisciplinary Systems Engineering*. Springer 105-127
38. JCIDS (2015) Manual for the operation of the joint capabilities integration and development system (JCIDS). *US Department of Defense. Washington. DC*
39. Schmidt, S. R. and Launsby, R. G. (2005) *Understanding industrial designed experiments*, Air Academy Press
40. BMT. *Global Wave Statistics*. (2011) [Accessed 2017] Available from: http://www.globalwavestatisticsonline.com/.
41. Morris, B. A., et al. (2018) An MBSE Methodology to Support Australian Naval Vessel Acquisition Projects. In: *Naval Postgraduate School - Acquisition Research Symposium,* Monterey, California
42. Saltelli, A., et al. (2004) *Sensitivity analysis in practice: a guide to assessing scientific models*, John Wiley & Sons
43. Zar, J. H. (1972) Significance testing of the Spearman rank correlation coefficient. *Journal of the American Statistical Association* **67** (339) 578-580

44. Spearman, C. (1904) Spearman’s rank correlation coefficient. *Amer J Psychol* **15** 72-101
45. Box, G. E. and Draper, N. R. (1987) *Empirical model-building and response surfaces*, John Wiley & Sons
46. IHS Jane's. (2017) [Accessed 2018] Available from: http://janes.ihs.com/janes/home.
47. IHS. *Jane's*. (2017) [Accessed Available from: http://janes.ihs.com/janes/home.
48. Buede, D. M. (2000) *The Engineering Design of Systems: Models and Methods*. New York, John Wiley & Sons Inc.
49. Stevens, S. C. and Parsons, M. G. (2002) Effects of motion at sea on crew performance: A survey. *Marine Technology* **39** (1) 29-47
50. Lackenby, H. (1954) On the presentation of ship resistance data. *Transactions of the Royal Institution of Naval Architects* **96** 471-497
51. Telfar, E. V. (1962-1963) The design presenation of ship model resistance data. *Transactions of the North East Coast Institution of Engineers and Shipbuilders* **79** 357-390
52. Bentley Systems Inc. *MAXSURF*. (2018) [Accessed 2018] Available from: https://www.bentley.com/en/products/product-line/offshore-structural-analysis-software/maxsurf.

Appendix A Hullform Definition Using Orca3D

The following figures detail the hullform design variables used within the Hullform and Geometry Model introduced in Section 2.2.1 and outlined in Table 1. Hullform design variables are those employed by the Orca3D ship hull design plugin for use with Rhinoceros Version 5.0.

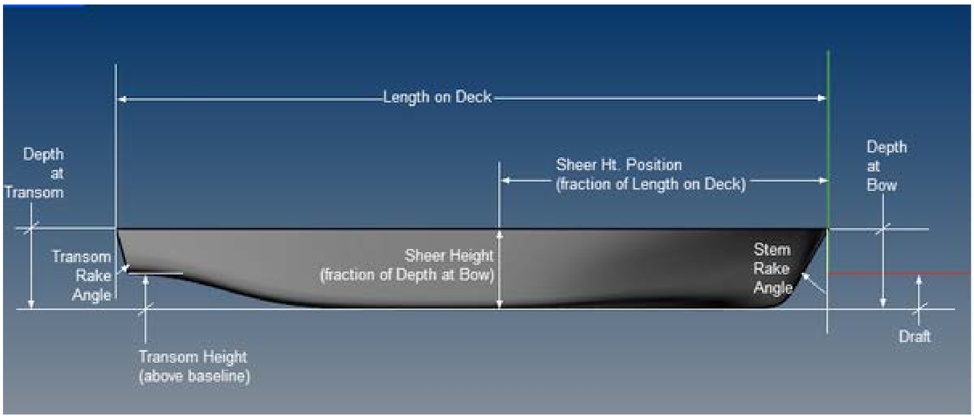

Figure A1. Profile view detailing the following hull design variables: Length, Depth, Transom Rake, Transom Height and Stem Rake.

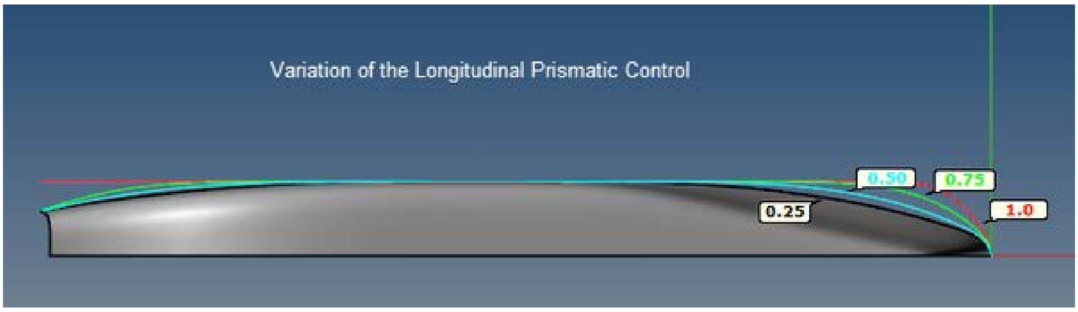

Figure A2. Plan view detailing use of the Prismatic Control hull design variable

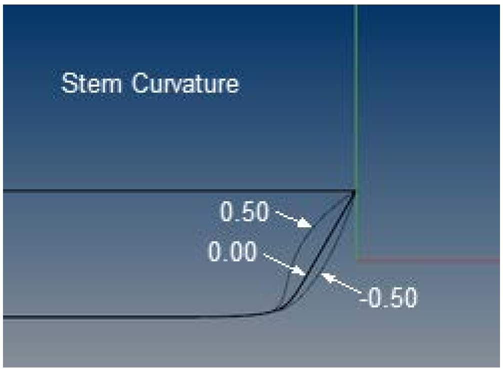

Figure A3. Profile view detailing use of the Stem Curvature hull design variable

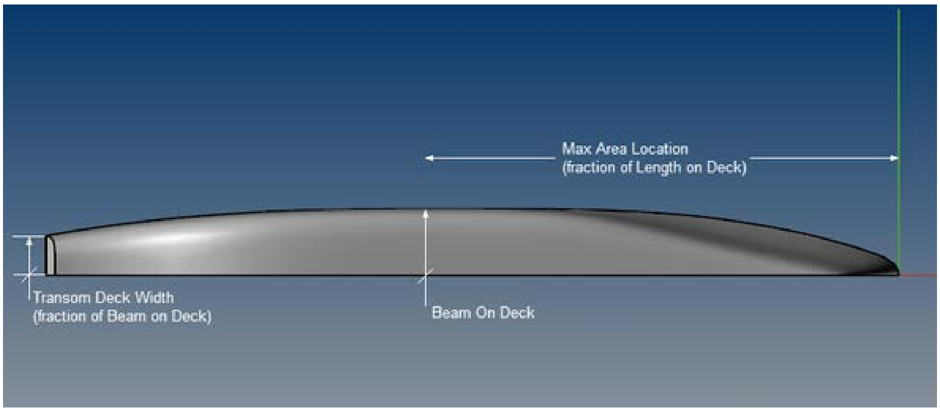

Figure A4. Plan view detailing the following hull design variables: Max Area Location, Beam (used for L/B) and Transom Deck Width.

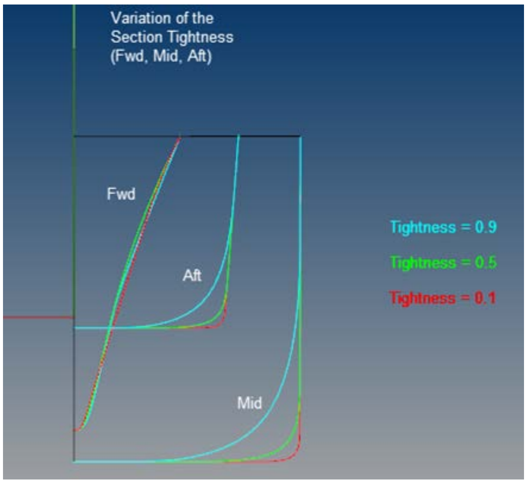

Figure A5. Body Plan view detailing use of the Section Tightness Aft, Mid and Fwd hull design variables

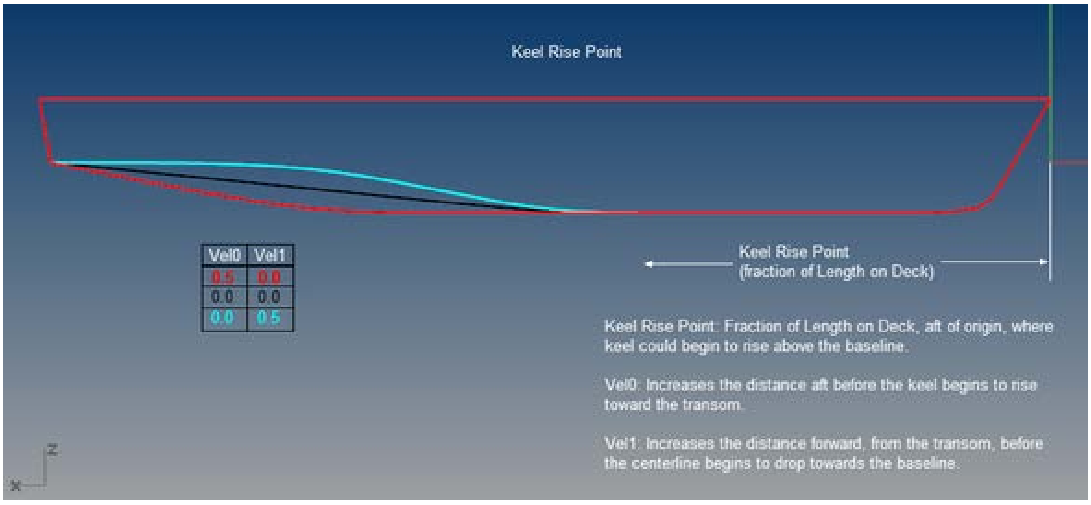

Figure A6. Profile view detailing use of the Keel Rise Point hull design variable

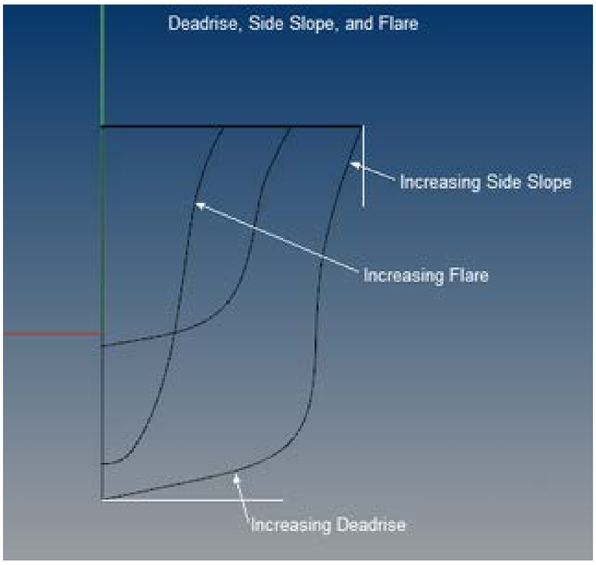

Figure A7. Body Plan view detailing the following hull design variables: Deadrise Aft, Mid and Fwd; Side Slope Aft, Mid and Fwd; Flare Aft, Mid and Fwd

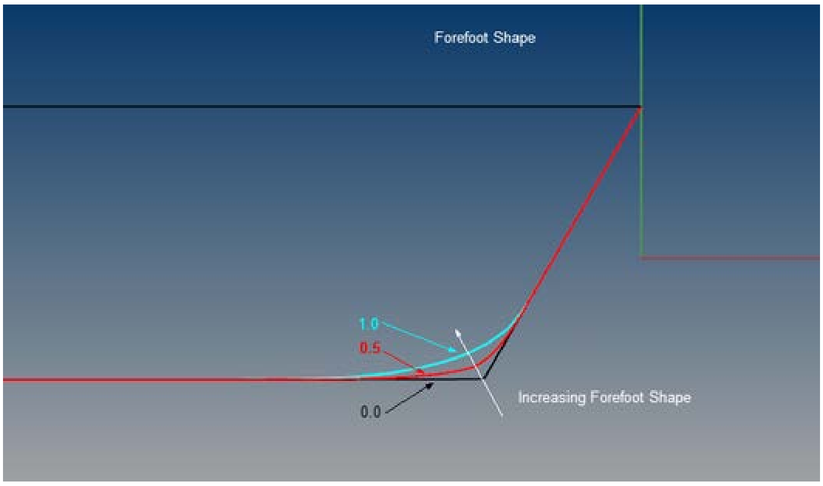

Figure A8. Profile view detailing the use of the Forefoot Shape hull design variable

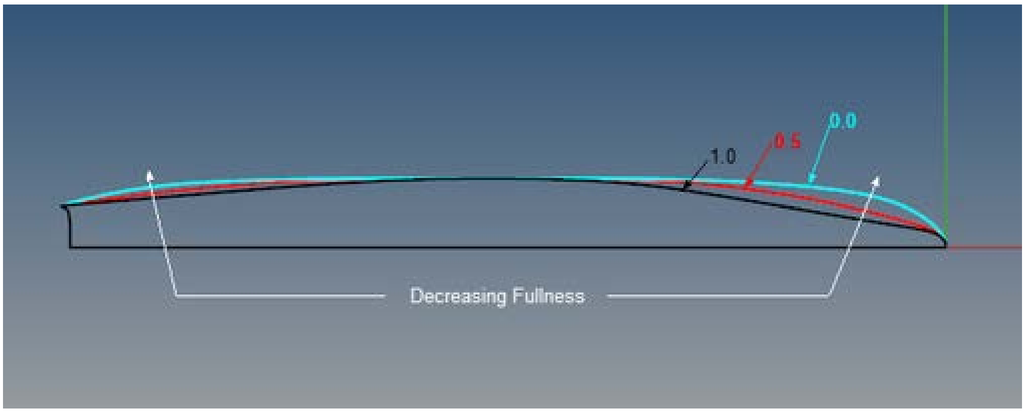

Figure A9. Plan view detailing the use of the Fullness hull design variable

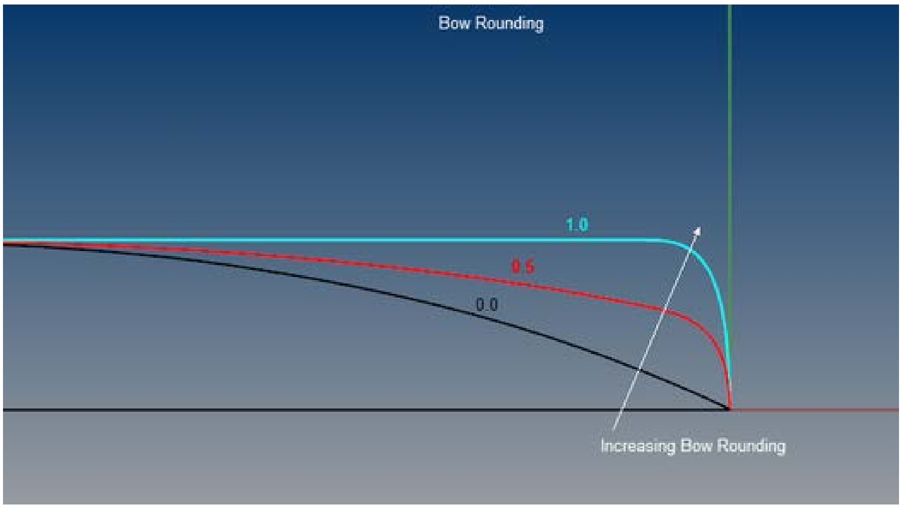

Figure A10. Plan view detailing the use of the Bow Rounding hull design variable

Appendix B Detailed Description of Key Performance Parameters

B.1 Launch & Recovery and Transit Seakeeping Operability Indices

Seakeeping operability indices are calculated using Equation 1 described in Section 2.2.4 of the report. Determination of seakeeping operability inputs are based on the guidelines provided by [33]. The necessary inputs to calculate a seakeeping operability of a specific attribute are as follows:

- Speed profiles – profiles are represented as discretised probabilities associated to a subset speed within the ships entire speed profile
- Heading profiles – profiles are represented as discretised probabilities associated to discrete headings within a 360 degree range of headings
- Seakeeping criteria – criteria are based on the type of tasks needed to be performed by the vessel. Depending on the task, criteria are assigned motion limits and a specific location on the vessel for which they are to be assessed.
- Criteria weightings – after criteria are defined they are assigned weightings which govern the relative importance of each criteria, and therefore the associated tasks.

Figure B1 shows the speed profiles that were used for both the Launch & Recovery (L&R) and transit seakeeping operabilities. As can be seen, it was assumed that the ship would be spending a majority of time in the low speed ranges during L&R activities. Conversely, it was assumed that during transiting the ship would be spending a majority of time above 10 knots.

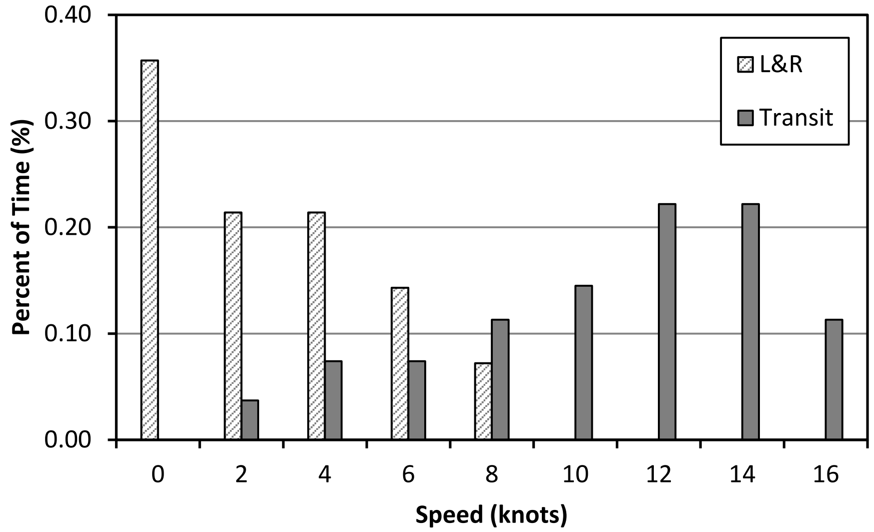

Figure B1. L&R and transit speed profiles for the example hydrographic survey capability

For the example hydrographic survey capability an equal heading distribution was assumed from a heading of 0 degrees (following seas) to 180 degrees (head seas) as per Figure B2.

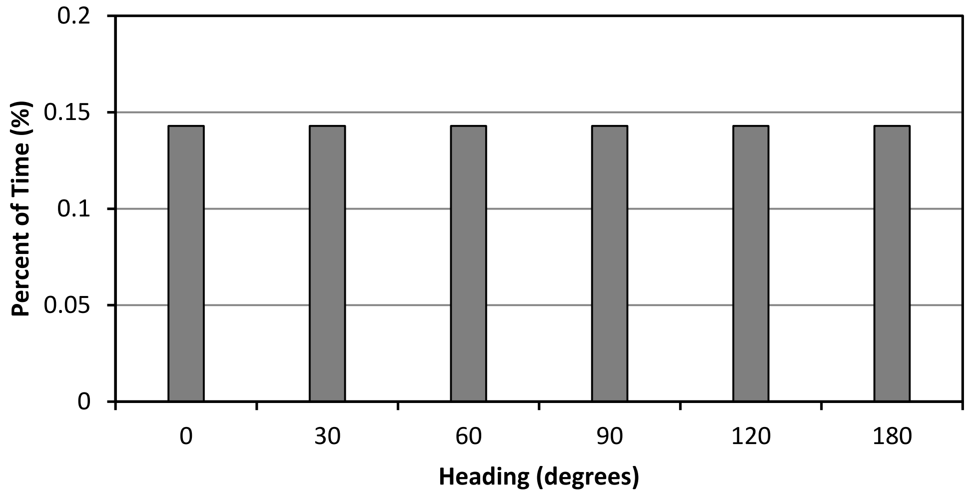

Figure B2. Heading profile for the example hydrographic survey capability

Criteria are referenced to a specific task, enabling that task to be performed correctly and safely. Criteria are then chosen based on the relation of each task which to be performed within each of the L&R and Transiting activities being assessed. The seakeeping criteria used for assessment of L&R and transit activities are depicted in Table B1 and include:

- Deck Wetness – the number of instances of green water on deck per hour

- Slamming – the number of significant slamming events (as defined by criteria limits) that occur per hour
- Motion Induced Interruptions (MII) – MIIs are defined as incidents where ship motions are large enough to cause a person to lose their balance unless they temporarily abandon their allotted task and adjust themselves to remain upright [49]. Measured as number of incidents per minute.
- Vertical Velocity – the velocities in m/s present in the vertical direction at a certain location due to the interaction between the ship and the wave environment
- Vertical Acceleration – the accelerations measured relative to gravity (2g is equivalent to two times the force of gravity) present in the vertical direction at a certain location due to the interaction between the ship and the wave environment
- Lateral Acceleration – the acceleration measured relative to gravity (2g is equivalent to two times the force of gravity) present in the lateral direction at a certain location due to the interaction between the ship and the wave environment

Table B1. Criteria: Launch and Recovery (L&R), Transit (Tr), and the respective locations where they were assessed

	Locations			
Criteria	**Bow**	**Bridge**	**Midship Deck Edge**	**Aft Helo Deck**
Deck Wetness	L&R, Tr		L&R	
Slamming	Tr			
MII		L&R, Tr	L&R	L&R
Vertical Velocity				L&R, Tr
Vertical Acceleration			L&R	L&R, Tr
Lateral Acceleration				L&R, Tr

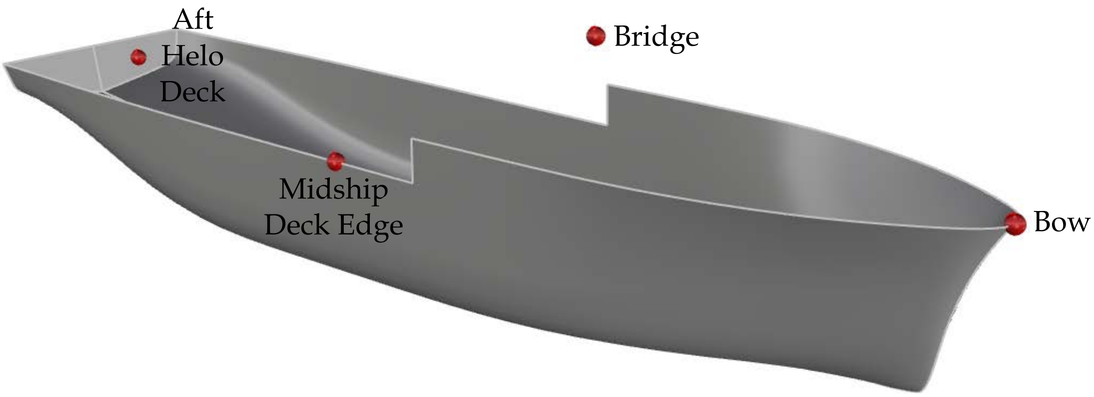

Figure B3 Representation of the four locations used for assessing the seakeeping operability indices

Limits used for each criterion for both L&R and transit activities and associated tasks for which the limits are derived and referenced to are detailed in Table B2.

Table B2. Limits and tasks associated with each criterion assessed and the activity (L&R or Transit) they are referenced to

Criteria	Task	Activity	Limit
Deck Wetness	Operational Transit	L&R, Tr	30 (per hour)
Slamming	Operational Transit	Tr	20 (per hour)
MII	Operational Transit	Tr	1 (per minute)
MII	Boat/ROV/Equipment Launch and Recovery	L&R	0.5 (per minute)
Vertical Velocity	Helicopter/VTOL/STOVL	L&R, Tr	2 (m/s)
Vertical Acceleration	Helicopter/VTOL/STOVL	L&R, Tr	0.2 (g)
Lateral Acceleration	Helicopter/VTOL/STOVL	L&R, Tr	0.125 (g)

Figures B4 and B5 show the criteria weightings used for the transit and L&R seakeeping operabilities respectively. Weightings were applied for each criteria at every location the criteria was assessed. Equal weightings were applied to each criterion with the assumption that for the hydrographic survey capability, no single task to be performed for a given activity had more importance over any other. Of course, through stakeholder engagement, preference for certain activities can be deliberated and weightings applied accordingly to represent stakeholder needs.

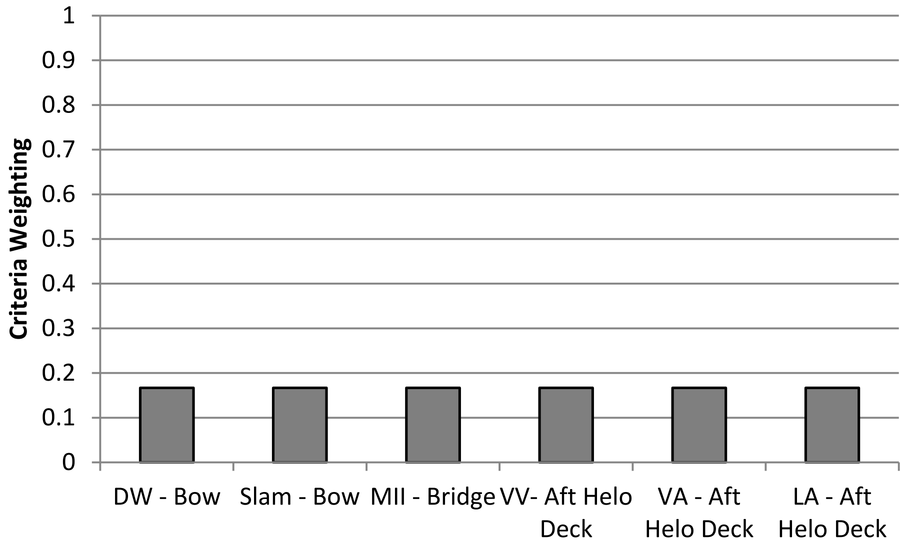

Figure B4. Weightings for each criterion at their respective locations for the transit seakeeping operability; Deck Wetness (DW), Vertical Velocity (VV), Vertical Acceleration (VA) and Lateral Acceleration (LA)

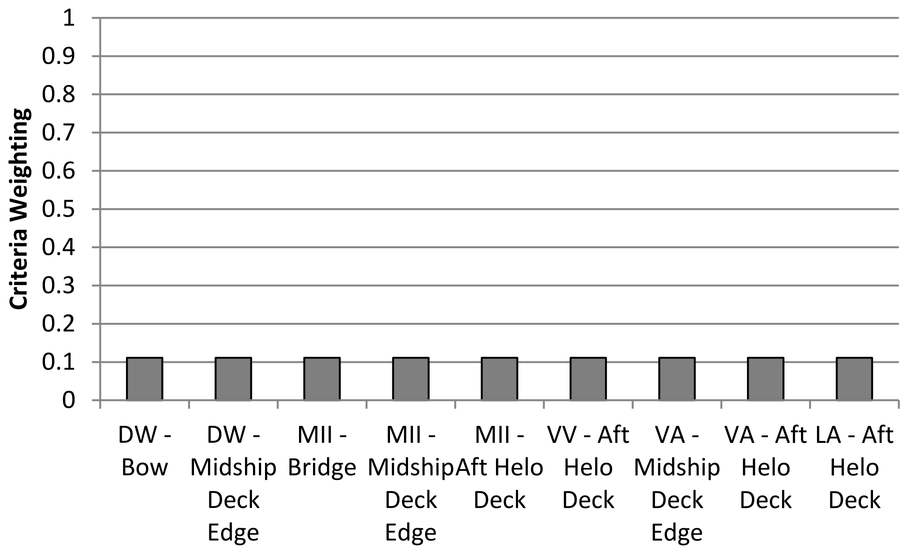

Figure B5. Weightings for each criteria at their respective locations for the L&R seakeeping operability; Deck Wetness (DW), Vertical Velocity (VV), Vertical Acceleration (VA) and Lateral Acceleration (LA)

B.2 Total Resistance per tonne Displacement at Transit Speed (14 knots)

Lackenby [50] and Telfar [51] propose that total resistance (R_T) per tonne of vessel displacement (Δ) is a suitable method for comparing hull designs of different forms and displacements. This comparative measure can be interpreted as a Total Resistance per tonne Displacement (R_T/Δ) measure.

The total resistance is determined by summating the calm water and added resistance in waves. From Section 2.2.2, calm water resistance is based on the prediction method originally introduced by Holtrop and Mennen [28]. Added resistance in waves is determined for head seas in the respective wave conditions introduced in Section 3.3.1.

The Key Performance Parameter for R_T/Δ used for analysis throughout this report considered only a single speed. This speed was chosen as the design transit speed, which was 14 knots. The transit speed was chosen since the ship would be designed to operate efficiently at this speed for a majority of its service life, therefore representing a critical design measure.

Appendix C Software Applications comprising the Ship Performance M&S Framework

C.1 ModelCenter

ModelCenter is a model-based engineering software application developed by Phoenix Integration [25]. ModelCenter has two key functions that are fundamental for the application of the Ship Performance M&S framework: integration and exploration. The integration functionality allows users to [25]:

- *Automate any modelling and simulation tool from any vendor* – allows the integrated use of the following modelling and simulation tools, see Sections C.2, C.3, C.4 and C.5.
- *Integrate these tools together to create a repeatable workflow* – different tools are integrated together into a flowchart allowing data to be transferred between them.
- *Set simulation parameters* – after workflows are established the simulation can be further tailored by setting any range of input parameters.
- *Automatically execute the workflow* – workflows can be executed under the guidance of a single workflow execution or more complex multi-run trade studies.

Furthermore, the exploration functionality allows users to:

- *Run powerful algorithms and trade study tools* – efficiently generate a design space in a robust and reliable manner.
- *Search, investigate and understand the design space* – identify and understand relationships with the use of design space exploration tools.
- *Incorporate multiple variables* – perform trade-offs by direct comparison of input and/or output variables.
- *Visualize results and the impact of design changes* – develop a clear picture of the results and relationships through a number of scientific visualization techniques.

C.2 MAXSURF

MAXSURF is a naval architecture based suite of software applications for the development of initial marine vessel design. MAXSURF includes capabilities for hull modelling, stability, motions and resistance prediction [52]. Furthermore, MAXSURF has extensive importing and exporting formats to allow 3D hull models to be interpreted by various other programs. Currently, MAXSURF is used within the Ship Performance M&S framework for hydrostatic and transverse stability predictions. Future plans for adding additional capability to the Ship Performance M&S framework will include implementing the capabilities of MAXSURF motions and resistance prediction.

C.3 SHIPMO7

SHIPMO7 is an updated strip theory based program for computing ship motions in regular and irregular seas [31]. The program is efficient and robust for predicting ship motions and loads in seas for slender vessels (where the L/B > 4) operating in moderate seas (up to sea state 7). These constraints make the program applicable for a majority of naval vessels including primarily frigates. SHIPMO supports computation of seakeeping characteristics for a range of operating conditions giving the user control over speeds, heading and wave spectra. Hullform, trim and mass definitions allow motions and sea loads to be predicted for a range of vessel types and loading conditions. Seakeeping results are collected for the range of input conditions and aggregated within the Ship Performance MS framework to produce comprehensive seakeeping operability indices. Additionally, added resistance in waves is predicted by SHIPMO to supplement the calm water resistance predictions, refer to C.5.1, and produce total resistance predictions for a range of operating conditions.

C.4 Microsoft Excel

Microsoft excel is utilised by the Ship Performance M&S framework as the main analysis tool. Models ranging from simple to complex are created in Excel's spreadsheet based analysis environment. Depending on their complexity, some models utilise Visual Basic for Applications (VBA) programming language to create Macro's for automating tasks. The primary benefit for using Excel as the main analysis tool for model development within the Ship Performance M&S framework is that it is quick and easy to integrate with ModelCenter. Furthermore, Excel is widely available, meaning models created within the program can be accessed and edited by the majority of Ship Performance M&S framework developers.

C.5 Rhinoceros 3D

Rhinoceros (Rhino) is a 3D CAD modelling program which creates geometry based on NURBS curves, surfaces, and solids, point clouds, and polygon meshes [26]. Rhino is used by the Ship Performance M&S framework to develop 3D ship hullform geometry. Once the ship hullform geometry has been created Rhino supports a number of exporting formats allowing the geometry to be interpreted by other various programs. Rhino also supports the programming language RhinoScript which allows users to add additional functionalities and automate tasks.

C.5.1 Orca3D

Orca3D is a plugin for Rhinoceros 3D providing a suite of naval architectural based assessment tools [27]. These tools include hull design and fairing, basic hydrostatic and intact stability predictions, and empirical speed/power predictions. The main use of Orca3D in the Ship Performance M&S framework is to generate 3D hulls (referred to as hullforms throughout this report). Within Orca3D, hulls can be generated based on a number of unique global and local hull design parameters, see Appendix A. Utilizing

Rhinoscript allows for the automatic generation of a hullform based on the input parameters. Furthermore, after a hull is generated a bare hull resistance prediction is completed to provide the associated calm water resistance to be aggregated into the total resistance prediction, refer to Appendix C.3.

DEFENCE SCIENCE AND TECHNOLOGY GROUP DOCUMENT CONTROL DATA				1. DLM/CAVEAT (OF DOCUMENT)	
2. TITLE A Ship Performance Modelling and Simulation Framework to Support Design Decisions throughout the Capability Life Cycle: Part 1 – Risk Mitigation and Requirement Setting			3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED LIMITED RELEASE USE (U/L) NEXT TO DOCUMENT CLASSIFICATION) Document (U) Title (U) Abstract (U)		
4. AUTHOR(S) Dylan M. Dwyer and Brett A. Morris			5. CORPORATE AUTHOR Defence Science and Technology Group 506 Lorimer Street Fishermans Bend, VIC. 3207		
6a. DST GROUP NUMBER DST-Group-TR-3532	6b. AR NUMBER AR-017-284		6c. TYPE OF REPORT Technical Report	7. DOCUMENT DATE September 2018	
8. OBJECTIVE ID	9.TASK NUMBER 17/566			10.TASK SPONSOR HNE	
11. MSTC Maritime Platform Performance			12. STC Naval Architecture and Platform Systems Analysis		
13. DOWNGRADING/DELIMITING INSTRUCTIONS			14. RELEASE AUTHORITY Chief, Maritime Division		
15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT *Approved for public release* OVERSEAS ENQUIRIES OUTSIDE STATED LIMITATIONS SHOULD BE REFERRED THROUGH DOCUMENT EXCHANGE, PO BOX 1500, EDINBURGH, SA 5111					
16. DELIBERATE ANNOUNCEMENT No limitations					
17. CITATION IN OTHER DOCUMENTS Yes					
18. RESEARCH LIBRARY THESAURUS Modelling, Simulation, Ships, Performance evaluation, Design, Requirements					

19. ABSTRACT

Modelling and Simulation (M&S) presents the opportunity to support Australian Department of Defence endeavours toward becoming a smarter buyer in naval vessel acquisitions. Evaluating ship performance using M&S allows capability design activities to be conducted early during the Risk Mitigation and Requirement Setting phase of the Australian Capability Life Cycle (CLC). These activities support an improved understanding of a design space based on robust analysis that can be used by acquisition stakeholders to develop requirements and aid defensible design trade-off decisions. This report proposes an M&S framework for evaluating ship performance in support of Royal Australian Navy acquisitions. The M&S framework facilitates generation of an indicative design space for a defined capability need. Exploring this design space, acquisition stakeholders gain knowledge of a more thorough definition of requirements. Implementing the M&S framework ensures that the requirements released to industry, the primary output of this phase of the CLC, constrains the technical solutions to only those Off-the-Shelf designs that adequately meet the capability need. Thereby, the M&S framework can contribute to Defences ambition of becoming a smart buyer in an Off-the-Shelf naval vessel acquisition.